Optimization of hybrid 2-dimensional navigator correction to suppress respiratory-induced physiological noise

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Introduction

Blood oxygenation level-dependent (BOLD) functional MRI acquired using echo-planar imaging (EPI) is sensitive to magnetic field inhomogeneities induced by subject respiration, which are especially problematic at high fields where increases in physiological noise diminish gains expected from increased BOLD contrast-to-noise ratio [1]. Several techniques have been proposed to compensate for respiratory-induced physiological noise (RIPN), but not all approaches are able to correct local fluctuations in field inhomogeneities. Hybrid 2D navigator correction [2] is a technique recently proposed for multi-shot EPI that maps local fluctuations in the magnetic field after each radiofrequency pulse. Our goal was to quantify the improvement of hybrid 2D correction over the current technique used in our lab (1D navigator correction), and to identify the optimal parameters to reduce RIPN.

Methods

A noise measurement experiment was performed on a Varian *Unity* INOVA whole-body 4 Tesla MRI scanner (Palo Alto, CA) with a Siemens Sonata gradient coil (Erlangen, Germany). A single mid-axial slice was selected, and a T_2^*-weighted 2-shot centre-outwards 64 x 64 EPI sequence (TE = 15 ms, TR = 500 ms, FOV = 19.2 cm, θ_E = 42°, Thk = 6 mm, read gradient in the anterior-posterior direction) was used to acquire 480 resting-state images during an 8-minute scan. The participating subject provided written informed consent with a protocol approved by the university Human Subjects Research Ethics Board.

External physiological monitoring equipment was not used because it has been shown that the respiration cycle may be extracted simply from the phase of the center of k-space [3] (i.e., the global navigator). The following analyses were performed using custom software written in MATLAB 7.0 (MathWorks, Natick, MA). The normalized power spectrum density (PSD) of the global navigator revealed the respiration peak to be at 0.26 Hz with 28% of the noise power within a 0.1 Hz bandwidth. To avoid regions of signal void, a minimum pixel signal-to-noise ratio of 10:1 was set, resulting in an image mask consisting of 1508 pixels. Before the images underwent navigator correction, the area under the normalized PSD between 0.21 Hz and 0.31 Hz was computed for each pixel to measure RIPN with no correction. The same area under the PSD was then calculated for each pixel after navigator correction, and the ratio of the area after correction to before correction (denoted as β) measures the effect of navigator correction on RIPN. If $\beta < 1$, then navigator correction decreased RIPN for that pixel. The mean and standard deviation of β across the image mask (denoted as μ and σ, respectively) are used to gauge the performance of navigator correction techniques.

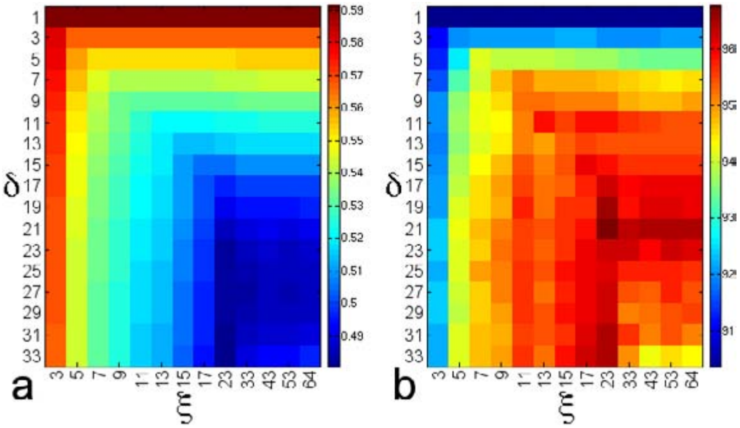

Figure 1: For each value of δ and ξ: (**a**) ratio of estimated RIPN after 2D correction to no correction; and (**b**) percentage of pixels in the image mask with reduced RIPN after 2D correction. Values of δ = 21 and ξ = 23 are appropriate choices to suppress RIPN.

Hybrid 2D navigator correction was employed to correct the center $\delta \times \delta$ region of k-space. The following modifications were made to the previously described implementation [2]: hybrid 2D correction was performed on data already processed by 1D navigator correction; 1D navigator correction was employed on the periphery of k-space; the image with the smallest absolute phase at the center of k-space was selected as the reference image; and a $\xi \times \xi$ region at the center of k-space was used to estimate 2D spatial changes in the magnetic field from the reference image (ΔB). As the performance of hybrid 2D correction is dependent on δ and ξ, 17 values of δ (= 1, 3, 5, …, 31, 33) were considered for 13 values of ξ (= 3, 5, 7, 9, 11, 13, 15, 17, 23, 33, 43, 53, 64), resulting in 221 correction configurations.

Results

Figure 1a displays the value of μ for each δ (rows) and ξ (columns). The use of 1D navigator correction results in μ = 0.592 (σ = 0.335), so a value of μ less than this represents an improvement over 1D correction. There is a trend towards decreasing μ as both δ and ξ increase, with δ = 17 and ξ = 23 (μ = 0.499, σ = 0.286) marking the point of diminishing returns in the reduction of RIPN. The minimum occurs when δ = 23 and ξ = 23 (μ = 0.482, σ = 0.285). Figure 1b shows a plot of the percentage of pixels in the image mask where $\beta < 1$ (denoted as P) as a function of δ and ξ. As before, there is a trend of increasing P as δ and ξ both increase. With 1D correction, P = 90.5%. The maximum value of P = 96.8% occurs when δ = 21 and ξ = 23. Interestingly, a similar value of P = 96.3% occurs when δ = 17 and δ = 23 (with ξ = 23). To visualize the reduction of RIPN through navigator corrections, the normalized time course of a single gray matter pixel in the parietal lobe with no correction, 1D correction, and 2D correction (δ = 21 and ξ = 23) is shown in Fig. 2.

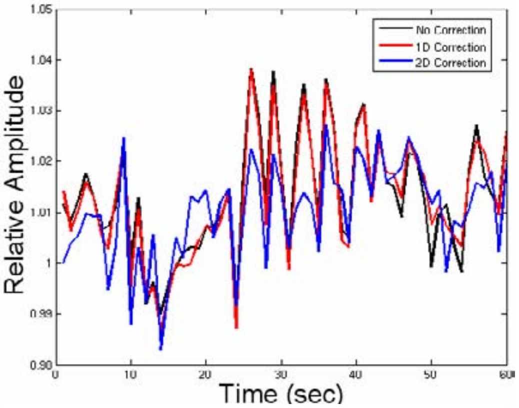

Figure 2: Time series for a gray matter pixel showing the effect of respiration, and the application of 2D navigator correction to reduce these undesired fluctuations.

Discussion

Values of δ = 17 and δ = 23 correspond to correcting spatial frequencies of ±0.42 cm^{-1} and ±0.57 cm^{-1}, respectively. For $\delta \geq 17$, increasing ξ past 23 slightly decreases the performance of 2D correction. Field inhomogeneities induced by respiration are primarily low-frequency, so the inclusion of spatial frequencies higher than ±0.6 cm^{-1} only adds extraneous thermal noise to the estimation of ΔB and explains the increase in μ for $\xi > 23$. For the same reason, correcting spatial frequencies higher than ±0.6 cm^{-1} does not translate into further reduction of RIPN. The approximate correction time per image (executed on a 1.6 GHz single-processor desktop) just exceeds one minute for δ = 23 and is less than half a minute for δ =17, with most of the computational resources spent calculating the pseudo-inverse of a complex encoding matrix. Thus, a value of δ between 17 and 21 is an appropriate compromise between correction accuracy and time. Furthermore, as the correction of one image is independent of any other image, parallel processing may be used to further reduce the overall computation time. In comparison to 1D correction, hybrid 2D correction provides an additional 11% improvement in the reduction of RIPN across the brain with 6% more pixels benefiting from reduced RIPN. Future work will apply hybrid 2D navigator correction to other functional data sets and investigate the improvement that this technique has on statistical activation maps.

References

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