Modeling of physiological noise in functional MRI due to respiration and suppression using navigator echo corrections

R. L. Barry[1,2], R. S. Menon[1,3]

[1]Laboratory for Functional Magnetic Resonance Research, Robarts Research Institute, London, Ontario, Canada, [2]Department of Biomedical Engineering, University of Western Ontario, London, Ontario, Canada, [3]Department of Diagnostic Radiology and Nuclear Medicine, University of Western Ontario, London, Ontario, Canada

Introduction

The measurement and suppression of physiological motion caused by the respiratory and cardiac cycles are of great importance in fMRI, more so at 3 T and beyond, where the mechanisms at play can reduce the statistical gains one might expect on the basis of the increased signal-to-noise ratio (SNR). The fluctuations in the local magnetic fields manifest themselves as dynamic off-resonance effects that distort the acquired MR image, and since it is observed that physiological noise increases with field strength, they are likely the dominant noise source contributions in high-field fMRI [1]. In terms of actual strategies used to remove dynamic off-resonance effects, Hu *et al.* showed that a global navigator echo may be acquired after each RF pulse in a fast low-angle shot (FLASH) sequence, and then be used to track the respiration cycles and to partially correct for frequency offsets due to respiration [2]. While the global navigator is relatively straightforward to implement, the merits of such a correction have not been examined closely. Our goal is to determine the relative contribution of dynamic off-resonance effects to the fMRI signal intensity fluctuation as a function of field strength, and to examine the global and 1-dimensional (1D) navigator echo correction strategies for reducing respiratory noise.

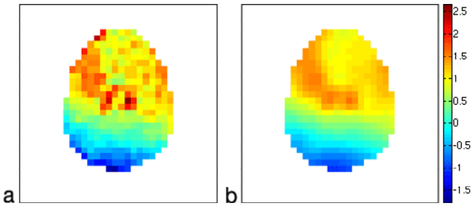

Figure 1: (**a**) Spatial FOM for the axial image calculated using RASTAMAP at inhalation and exhalation; a negative frequency (in Hz) indicates the frequency is higher at exhalation. After post-acquisition processing, (**b**) is the FOM used in the simulated signal acquisition.

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). The canonical model of a 2D anatomical brain image used in this research was constructed from a 256 x 256 high-resolution T_2^*-weighted axial image acquired using a magnetization-prepared (MP) FLASH sequence (TE = 15 ms, TR = 22 ms, $\alpha = 10^\circ$). By studying this image and its corresponding histogram, the range of pixel intensities corresponding with CSF was easily distinguished from the range of pixel intensities corresponding to the gray and white matter in the rest of the brain. Assuming that the proton density for gray and white matter are approximately the same, changes in contrast within and between these tissues may be attributed only to slight variations in T_2^* from one voxel to the next. The relative intensities in the FLASH image were used to convert each voxel from an intensity to a T_2^* value, using the fact that previous experiments at 4 T have shown an average T_2^* = 31.5 ms for gray matter [3]. To model the effect of respiration on the image acquisition, RASTAMAP was used to acquire static 32 x 32 x 32 3D field maps of the brain during a breath-hold after inhalation and exhalation [4]; the subtraction of these field maps revealed the respiratory-induced frequency offset map (FOM) in the brain. The temporal modulation of these spatial frequency offsets was modeled as a sinusoid with a period of 5 sec (approx. one respiration cycle). A 2-shot 128 x 128 EPI sequence is simulated (TE = 30 ms, TR = 525 ms) to investigate the effects of the FOM on the reconstructed images in an fMRI experiment. The entire navigator echo line is acquired after each simulated RF pulse, and the global [2] and 1D [5] navigator echo corrections are applied to the acquired data.

Results

The data presented in Fig. 1 demonstrate very clearly that the dynamic frequency offsets that occur during respiration cannot be assumed to be global in nature, even in an axial slice. Negative frequencies between about –1.0 Hz and 0 Hz were observed only in the bottom quarter of the FOM with a relatively wide horizontal band of near-zero frequency offsets approximately one-third from the bottom of the map. Positive frequencies between about 0 Hz and 1.5 Hz were observed in the top half of the FOM. Two regions of interest (ROIs) were selected in distinct regions of gray matter, corresponding to areas of 2.34 x 2.34 mm^2. The frequency offsets in ROI #1 and ROI #2 are 0.95 Hz and 1.4 Hz, respectively, and result in peak-to-peak signal intensity fluctuations of about 1.2% and 4.9% without navigator echo correction. Plots of the percentage signal fluctuation for ROI #1 are shown in Fig. 2 with the read gradient applied along the direction with the (a) least and (b) most spatial variation, with reference to Fig. 1b.

Discussion

In Fig. 2a, the change in mean signal intensity was 1.16% without phase correction, and 2.02% and 2.06% with global and 1D navigator echo correction, respectively. The amplification of the respiratory noise after phase correction illustrates the fact that the global and 1D navigator echoes are estimates of the frequency offsets over the whole image, which clearly do not accurately represent and correct for local frequency offsets within an ROI. The directions of the gradients are reversed in Fig. 2b. The change in mean signal intensity is then 0.32% without phase correction, 1.85% with global navigator echo correction, and 0.17% with 1D navigator echo correction. In ROI #2, the signal intensity fluctuation was 4.88% without phase correction, 2.95% with global navigator echo correction, and 0.96% with 1D navigator echo correction for orientation (b) of the read and phase encode gradients. These fMRI simulations have shown that reasonable frequency offsets due to respiratory noise between can cause fluctuations between about 1% and 5% in signal intensity without phase correction, and that global or 1D navigator echo correction may over-compensate and amplify this noise in ROIs that experience local frequency offsets that are significantly different from the estimated frequency offsets measured using the navigator echo line. The read gradient should be set along the direction with the most spatial variation so the 1D navigator echo better estimates the frequency offsets along the direction with the least spatial variation. Finally, 1D navigator echo correction is preferable to global navigator echo correction for the improvement of the suppression of physiological noise due to respiration. However, it is also quite clear that full 2D navigator echo correction would be even more advantageous.

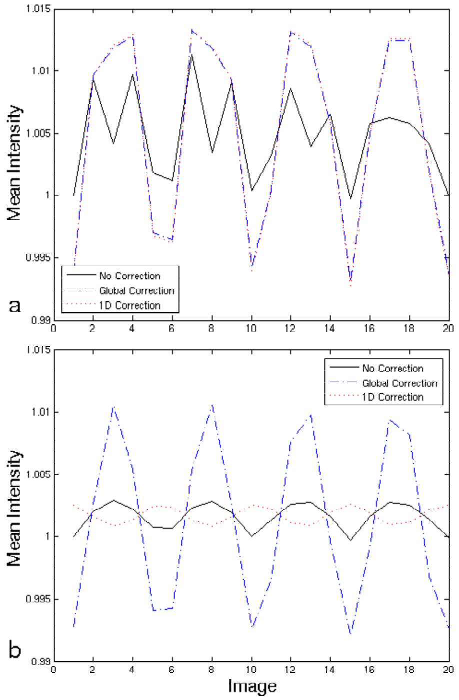

Figure 2: Normalized change in mean pixel intensity for an ROI in an fMRI simulation with no navigator echo correction, global navigator echo correction, and 1D navigator echo correction, for the orientations (**a**) and (**b**) of the read and phase-encode gradients.

References

[1] Kruger G, Glover GH. Physiological noise in oxygenation-sensitive magnetic resonance imaging. MRM 2001;46:631-637.
[2] Hu X, Kim S-G. Reduction of signal fluctuation in functional MRI using navigator echoes. MRM 1994;31:495-503.
[3] Gati JS, Menon RS, Ugurbil K, Rutt BK. Experimental determination of the BOLD field strength dependence in vessels and tissue. MRM 1997;38:296-302.
[4] Klassen LM, Menon RS. Robust automated shimming technique using arbitrary mapping acquisition parameters (RASTAMAP). MRM 2004;51:881-887.
[5] Ehman RL, Felmlee JP. Adaptive technique for high-definition MR imaging of moving structures. Radiology 1989;173:255-263.