

Combined interactions of respiratory and cardiac signals measured by high-temporal resolution fMRI

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Introduction

In fMRI studies, BOLD signal changes are often characterized by a low signal-to-noise ratio (SNR). Physiological artifacts such as cardiac and respiratory noise constitute an important confounding factor that may prevent the detection of significant activations. Moreover, the relatively low temporal resolution of standard fMRI acquisitions cannot adequately sample the artifactual signals, which then become aliased in lower frequency bands. Improvements in SNR have been noted after the removal of low-order aliased harmonics of the cardiac and respiratory frequencies, but a proper characterization and removal of the physiological artifacts requires a higher temporal sampling rate to reduce aliasing effects. The current study investigates the effect of physiological noise in MR-encephalography (MREG), an under-sampled parallel fMRI acquisition method with extremely high temporal resolution. This allows the examination of the effect of high-order harmonics of the cardiac and respiratory signals on the fMRI data, as well as interactions between the two types of physiological artifacts.

Methods

Under-sampled radial data from 7 healthy volunteers were acquired on a 3T Tim Trio scanner (Siemens, Erlangen, Germany) using a custom-built 8-channel surface head receiver coil array, with the coil elements arranged in a semi-circle around the visual cortex. The images were reconstructed by a regularized method with a temporal resolution of 80ms (Grotz et al., 2009). During the scan, subjects were presented with a reversing checkerboard stimulus for 20 seconds, alternating with 20-second periods of rest. The data were then analyzed in the general linear model (GLM) framework using SPM8 (Wellcome Trust Centre for Neuroimaging, London, UK). The visual activation signal was modeled as the convolution of the block stimulus with a canonical hemodynamic response function. The cardiac and respiratory artifacts were then modeled as quasi-periodic signals fitted by a Fourier series based on the phases of the cardiac and respiratory cycles corresponding to each image (Glover et al., 2000). The order of the Fourier series was determined by a stepwise regression in which successively higher harmonics were added to the model until they no longer reached statistical significance (F-test, $p < 0.05$ FWE, Bonferroni-corrected for the number of regression steps). Interactions between cardiac and respiratory artifacts were also studied by correlating the respiratory signal with the amplitudes of the principal components of the residuals in each cardiac cycle. These interactions were then modeled as modulations of the cardiac regressors by the respiratory regressors.

Results

For respiratory artifacts, Fourier regressors up to order 2 were associated with statistically significant clusters in all subjects. In some subjects, even higher-order regressors up to order 5 were also significant. For cardiac artifacts, Fourier regressors up to order 7 were significant in all subjects, with higher-order regressors also significant in some subjects up to order 10. The effect of the high-order terms was widespread; the percentage volume with a significant effect was 23% for respiratory regressors of order greater than 2, and 99% for cardiac regressors of order greater than 2. After removing these common fluctuations across the respiratory and cardiac cycles, a principal component analysis revealed that 69% of the studied brain voxels showed a correlation coefficient greater than 0.25 between the respiratory signal and the amplitude of the first principal component of the cardiac residuals (see Figure 1). This indicates that cardiac fluctuations were modulated by the respiration. In a GLM analysis, cardiac regressors of Fourier orders up to 7 and modulated by the respiratory signal were associated with statistically significant fMRI clusters accounting for an average of 81% of the studied brain volume. The addition of these modulation regressors resulted in small, but statistically significant ($p < 0.05$) increases in activation volumes (average 1.5%) and t-values (average 5.4%) related to the visual paradigm.

Discussion

The fMRI signal is confounded by significant cardiac and respiratory artifacts. These artifacts are aliased in standard fMRI acquisitions, but the current study shows that high-order harmonics account for a significant amount of signal variance and require a high temporal sampling rate for their adequate characterization and removal. Additionally, fMRI cardiac fluctuations were found to be significantly correlated with the respiratory amplitude in widespread areas. The modeling of this modulation effect only resulted in a modest increase in sensitivity for the detection of the BOLD response to the slow visual paradigm, but this could potentially have a higher impact for faster event-related paradigms near the respiratory frequency.

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References

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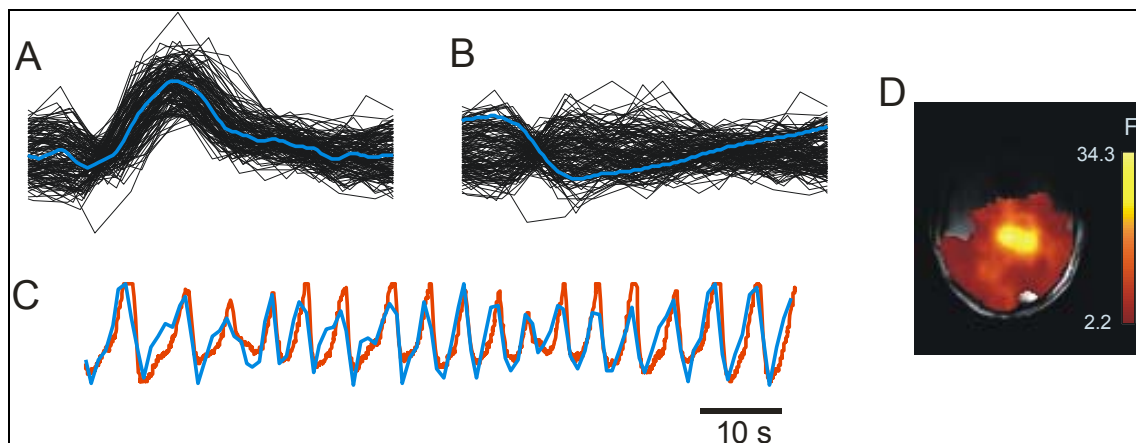


Figure 1. A: Superposition of the fMRI signal from each cardiac cycle for one selected voxel (black curves). The shape fitted by 10th-order Fourier regressors is shown in blue. B: Residuals from the previous fit (black curves), along with the first principal component of these residuals (blue curve). C: Amplitude of the first principal component across time for each cardiac cycle (blue curve), superimposed on the respiratory signal (red curve). The correlation coefficient between the two signals is 0.88. D: Regressors modeling the modulation of the cardiac signal by the respiratory signal show a significant effect in 93% of the studied volume.