Physiological noise reduction in spinal fMRI from a single-stage, motion-compensating GLM approach

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Introduction

Three-dimensional displacement of the human spinal cord has recently been measured in relation to the cardiac cycle, substantiating that cord motion itself is a likely cause of reduced sensitivity and specificity in functional magnetic resonance imaging of the spinal cord (spinal fMRI).[1] However, given the ubiquitous and complex nature of this motion, cardiac-gating is not expected to sufficiently remove these errors, while on the other extreme, previous attempts to model the noise are prone to eliminating function-related data along with the components of motion-related noise.[2]

As a first approach, motion-related confounds have been modeled and removed using a two-stage general linear model (GLM), verifying that errors in spinal fMRI can be reduced by fitting to a model of spinal cord motion.[3] In this manner, the components of signal fluctuation matching the modeled timecourse of spinal cord motion were subtracted (in the first stage) before reformatting sagittal data into cubic voxels, re-slicing into transverse volumes, and smoothing in the rostral-caudal direction. The motion-compensated, reformatted, and smoothed timecourse data were then fit to a boxcar model paradigm to identify the components of signal change resulting from neuronal activity (in the second stage). The two-stage approach was implemented initially to get around the problem of coalescing data from different cardiac phases during the reformatting step. However, while this approach demonstrated improved sensitivity and reliability (over previous analysis methods) as a result of modeling motion-related noise in a GLM, the two-stage process is not optimal, requiring lengthy data processing times, and suffering – albeit to a lesser degree – the problem of potentially eliminating functionally-relevant signal changes in the event that the motion and paradigm models are not completely linearly independent. To minimize data processing times and reduce the risk of Type II (false-negative) errors, we have streamlined the analysis into a single-stage motion-compensating GLM approach, which is described herein.

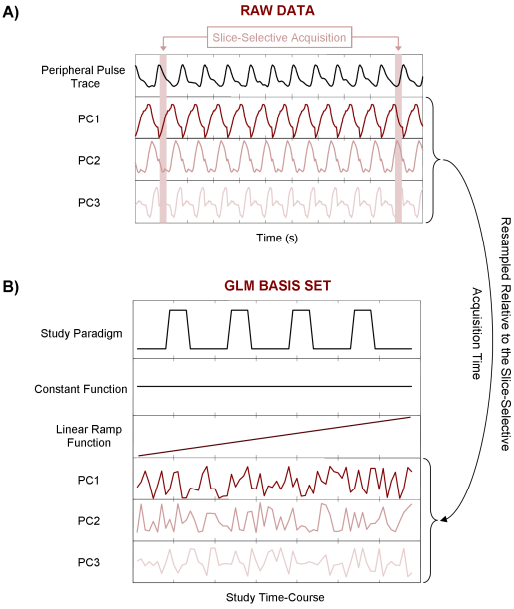

Figure 1: A typical basis set for one slice. Because each slice is acquired at a different phase of the cardiac cycle, each slice has a unique basis set with the principal components of spinal cord motion sampled appropriately to account for cardiac phase.

Methods

Development: The new single-stage analysis works by first defining a reference line along the anterior spinal cord, as previously reported.[2,3] However, instead of reformatting into cubic voxels and re-slicing the data into transverse segments, as in the two-stage GLM approach, rostral-caudal smoothing (parallel to the reference line) is performed within each sagittal slice. After smoothing, the timecourse data from each slice is individually analyzed by fitting to a slice-specific GLM composed of six basis functions (Figure 1B): a boxcar model paradigm, a constant function (to account for baseline intensity), a linear ramp function (to account for baseline drift), and each of three principal components (PCs) of spinal cord motion synchronized with the phase of the peripheral pulse trace and resampled with the slice-specific acquisition timing (Figure 1A). Thus, the functionally-relevant components of signal change are identified (at a given statistical significance) on a voxel-by-voxel basis within each slice.

Validation: To validate this approach, null-task spinal fMRI data were acquired from four healthy subjects (2 male, 2 female) using a 3T Siemens Magnetom Trio, and data were analyzed with the aforementioned method, as well as without motion-compensation. Because there was no task/stimulus, any apparent regions of activity are merely the result of noise, and a reduction in the number of active voxels (compared to uncompensated methods) indicates increased fidelity (i.e., lower false-positive rate, or ultimately, greater specificity) in detecting functionally-relevant, and not noise-related, signal intensity changes.

In addition, we have reanalyzed 100 data sets (from previous spinal fMRI studies) to evaluate the number of 'active' voxels, as well as the signal properties of those voxels (i.e., the mean signal change and standard deviation) to infer the sensitivity and specificity of our single-stage GLM compared to uncompensated methods. By identifying the number of active voxels, the relative sensitivity of each method can be evaluated, and since physiological noise and motion-related artifacts result in relatively large and quite variable signal intensity fluctuations, lowering the mean signal intensity change and signal variability (standard deviation) can be interpreted as reducing contributions from motion-related noise (i.e., improving the specificity to neuronal activation).

Results and Conclusions

By collecting null-task spinal fMRI data and reanalyzing one hundred previously acquired spinal fMRI data sets, we show that our single-stage GLM approach: 1) minimizes the occurrence of false-positives in null-task fMRI studies, 2) reduces the magnitude of signal change and signal variability (also interpreted as reducing false-positives) in actual spinal fMRI studies, and 3) increases the number of active voxels in spinal fMRI studies. Therefore, we have shown that modeling spinal cord motion in a single-stage GLM is an efficient and effective means of systematically removing motion-related noise from spinal fMRI, improving its specificity and sensitivity to neuronal function while minimizing data processing time.

References

1. C.R. Figley and P.W. Stroman. *Magn. Reson. Med.* 58:185-189 (2007).
2. P.W. Stroman. *Magn. Reson. Med.* 56:452-456 (2006).
3. C.R. Figley and P.W. Stroman. *Proc. Intl. Soc. Mag. Reson. Med.* 15:1951 (2007).