Removal of synergistic physiological motion and image artefacts in functional MRI of the human spinal cord

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Introduction

While physiological motion is a significant source of errors for fMRI in general, it is a particularly challenging problem for fMRI of the spinal cord.[1] This is a consequence of the location of the spinal cord within the spine, in close proximity to the heart and lungs, and because the cerebrospinal fluid around the cord moves with each heart-beat and causes the cord itself to move.[1] Previous studies of the characteristics of this motion have produced means of modelling motion-related confounds for inclusion in a General Linear Model, but this approach is only partially effective. The residual errors suggest that the motion-related confounds are more complex than the time-series of the CSF flow and cord movement, and arise from spatially and temporally variant image artefacts. The purpose of this study was to characterize these residual errors, model them, and remove them from fMRI data.

Methods

A computer simulation was developed to replicate the complete pulse sequence used for our established spinal fMRI method, namely, a half-fourier single-shot fast spin echo (HASTE) sequence, and model all inherent image artefacts, including those arising from motion (top panel of Figure). This simulation was applied to model the signal obtained from a region containing high-intensity transitions between two materials (to replicate the spinal cord and CSF intensity differences), and with periodic pulsatile flow of the high intensity region (to simulate CSF flow adjacent to the spinal cord). Simulations were calculated for a complete range of phases of the periodic flow cycle at the start of the single-shot imaging sequence, in order to replicate variations across the cardiac cycle.

Results and Discussion

The results of the simulation demonstrated Gibb's ringing at the high-intensity transitions, and artefactual movement of the regions undergoing periodic motion in the phase-encoding direction. The combination of Gibb's ringing and motion artefact creates an interference pattern within the regions adjacent to the simulated CSF flow, due to summation of signals with varying phases. The result is a complex signal fluctuation pattern which depends on position in the image, and phase of the cardiac cycle. We term this effect "CSF fog".

Given that the signal intensity fluctuations occur in the phase encoding direction only, and arise from Gibb's ringing in combination with phase errors, the effect was modelled as a convolution of an unknown distortion function, F, with the ideal signal intensity profile in phase encoding direction, S_{ideal} (i.e. in the absence of any artefacts)

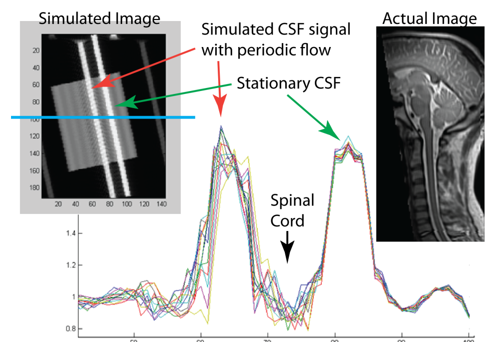
$$S_{observed} = F \otimes S_{ideal}$$

The "ideal" intensity profile, S_{ideal}, was estimated for real data (acquired from healthy participants, middle panel of Figure) by averaging all of the data across time points of the fMRI time series. The unknown distortion function was estimated for each time-point of the fMRI time series by deconvolution of the ideal profile, with the actual profile:

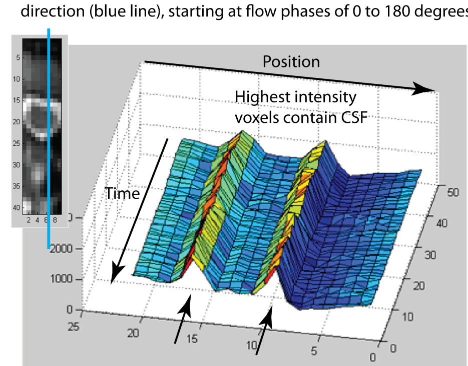
$$F = S_{observed} \otimes^{-1} S_{ideal}$$

The artefacts caused in each line of image data in the phase encoding direction, in each time point of the fMRI time series, were then modelled in this manner, and subsequently subtracted from the original fMRI time series to produce a data set with the CSF fog theoretically removed (bottom panel of Figure).

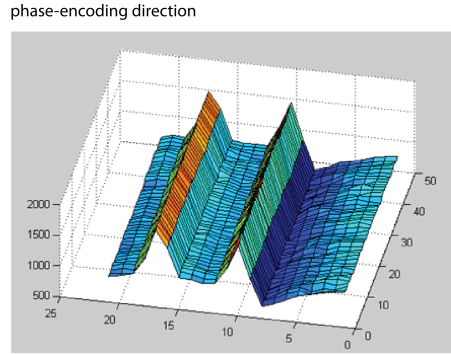
The effects of the "CSF fog" removal process were replicated in simulations to confirm that localized signal changes, due to neural activity in the spinal cord, would not be removed by this process. The resulting method was tested on real data obtained in "Null" studies, and in a "Test-Retest" study, and was confirmed to be effective at reducing the false-negative rate. Moreover, the CSF fog removal is most effective when combined with the previously described estimates of cord motion in the GLM.[1]



Simulations of signal intensity profiles in the phase-encoding direction (blue line), starting at flow phases of 0 to 180 degrees



Actual data: Intensity profiles through the spinal cord in the phase-encoding direction



Actual data after calculation and removal of "CSF fog"

Conclusions

An important effect of physiological motion and image artefacts has been identified, and an effective method for modelling and removing this confounding effect, termed "CSF fog", has been developed. This method provides improved reliability of spinal cord fMRI results.

References

1. Figley, C.R. & Stroman, P. W. *NeuroImage* **44**, 421-427 (2009).