Filtering Noise from fMRI Data Using the Stockwell Transform

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Abstract: We describe a novel technique for filtering temporal noise from fMRI data. The technique is based on the Stockwell Transform (ST), which provides the frequency content at each time point in a signal. After preliminary analysis of an fMRI data set, a GUI-based system is used to select regions of interest encompassing artifactual frequency/time-point components to filter. An inverse ST incorporating the filter is then applied to the whole image data set for subsequent reanalysis. This method successfully removes targeted artifacts while preserving the frequency components of the signal at all other time points.

Introduction: Physiological and electrical noise that contribute to temporal artifacts in fMRI data sets can occur at a variety of frequencies and time points. These artifacts can lead to false-positive activations or may cause significant activity to be missed. Commonly, Fourier Transform (FT) filtering techniques are used to remove or minimize these artifacts. These techniques target frequencies across the entire time series, potentially removing useful information from other time points in the data. The ST combines aspects of the Continuous Wavelet Transform (CWT) and the FT to provide a complete description of the frequency content at each time point in a signal. Furthermore, an inverse ST may be used to reconstruct the Fourier domain from the Stockwell domain. In this study, we used the ST to identify and remove transient artifacts from fMRI time series to help improve detection and quantification of activated brain areas.

Methods: A healthy female volunteer acted as a subject for this study. fMRI experiments were performed using a 3 Tesla MR imaging system (General Electric) with a quadrature birdcage head RF coil. T_2*-weighted images of 10 slices prescribed parallel to the calcarine sulcus were collected using multi-shot gradient-recalled EPI (TE = 30 ms, TR = 1000 ms, 2-shots, 24 cm FOV, 64x64, 5 mm thick) with navigator echoes to correct for phase fluctuations due to respiration. The subject wore liquid crystal display goggles (Resonance Technology, Inc.) connected to the video output of a personal computer. A 6-Hz flashing checkerboard was presented for 6 seconds (*activation phase*), immediately followed by 24 seconds of a static gray screen (*rest phase*). This was repeated 7 times. During separate experiments, the subject was asked to (i) take several deep breaths, (ii) cough lightly, or (iii) talk briefly during the 2nd activation phase and 4th rest phase. Image data were zero-padded to 128x128, and images were corrected for subject head motion.

A preliminary functional map of brain activity within the visual cortex was obtained from voxels significantly correlating with a modeled hemodynamic response function ($p < 0.01$, cluster size 4). The average timecourse of the voxels in the functional map was subjected to the ST producing a contour plot of frequency content versus time. Temporal artifacts were identified and encircled using a mouse and a graphic user interface designed in IDL[2]. ST values within these regions of interest were replaced with zeroes, and this result was applied as an inverse ST to the entire original image data set on a voxel-by-voxel basis. New functional maps were created at the same statistical threshold, corrected for changes in degrees of freedom. The amount of activation within the visual cortex (i.e., number of voxels times the average % increase in MR signal) was compared between the original data set and the newly ST-filtered data set, as well as for maps created using low-pass FT filtering to remove high-frequency noise.

Results: **Figure 1**

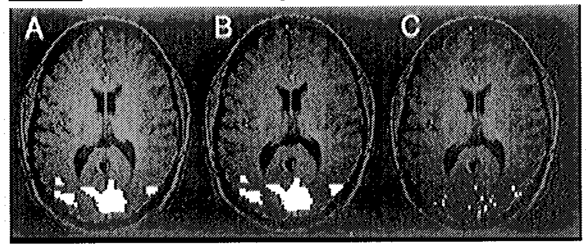

Figure 1 shows (A) a preliminary map, (B) a map obtained after ST filtering, and (C) a map showing the voxels in (B) but not in (A) for the experiment where the subject talked briefly during the 2nd activation phase and the 4th rest phase. ST filtering increased the number of detectable voxels within the visual cortex.

Table 1

	ST	lp-FT
breathe	+0.5%	+13.5%
talk	+5.1%	+17.4%
cough	+8.8%	+18.0%

Table 1 summarizes the change in amount of activation as a result of ST filtering and/or low-pass FT (lp-FT) filtering. The ST was effective in filtering artifacts due to coughing and talking. Although motion correction was used, ST filtering may correct for artifacts occurring due to motion outside of the field of view when coughing and talking (e.g., jaw movement, expelling of air). Upon inspection of voxel time courses, no appreciable breathing-related artifacts were observed as a result of the phase-based navigator echo correction. Hence, the ST filter had little impact on breathing artifacts. ST filtering also reduced the number of spurious activated voxels.

The change in activation using a low-pass FT was similar across all experiments due to the indiscriminant nature of the filter at high frequency. It is important to note if artifacts are correlated with the task (as in our case), FT filtering would smooth these artifacts across time, thereby strengthening their correlation with the modeled hemodynamic response function and increasing the number of falsely activated voxels. The use of global low-pass filtering after local frequency filtering (both of which can be accomplished through the ST) may be a good approach to remove uncorrelated high-frequency noise in addition to temporal artifacts.

Conclusion: While FT-based filtering techniques remove frequency components from the entire time series, the ST selectively removes frequencies based on operator input or by pre-specified threshold. Further assessment of the ST as a noise-filtering tool is needed. As well, an ST filter with no operator input would be more useful. This is under development. Nonetheless, our results demonstrate the usefulness of the ST for noise filtering fMRI data.

References:

1. Stockwell, R.G., *et al.*, *IEEE Trans. Signal Proc.*, 44, 998, 1996.
2. Fanning, D.W. *IDL Programming Techniques*, first ed., Fort Collins, USA: Fanning Software Consulting, 1999.

Supported by AHFMR, CIHR, Neuroscience Canada, and the MS Society of Canada. The authors wish to thank Dr. Louis Lauzon for his technical assistance and Mr. Andrew Tieman for his help and suggestions.