Physiological Noise Extraction in fMRI Data Using Empirical Mode Decomposition

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Introduction Physiological noise caused by ecg- and/or breathing related pulsatility is known to have substantial influence on the BOLD signal [1,2]. Such effects may introduce temporal correlations that are unrelated to neuronal processes in a resting-state network analysis [3]. Various noise removal techniques have been proposed, including image-based estimation schemes [4,5] and methods that use external ECG/respiration measurements as regression models such as RETROICOR [6].
Empirical mode decomposition (EMD) has been shown to have good performance on analyzing non-linear, non-stationary data [7]. It separates signals into intrinsic mode functions (IMFs) that are more likely to yield real physical meaning than simple filtering in the Fourier domain. In this study we implemented EMD on resting-state fMRI time-series and extracted cardiac components, then compared it's time-frequency curve with ECG recordings. Fixed band-pass filtering and RETROICOR results were also obtained for comparison.

Methods Three resting-state fMRI measurements were performed on a 3.0T Magnetom Trio scanner (Siemens Healthcare, Erlangen, Germany). Data of 112x112x6 matrix size were acquired with an FOV of 224x224x30 mm and TR/TE = 360/25 ms. External ECG signals were recorded parallel to the fMRI scan with 400 Hz sampling rate. Subject heart rate as a function of time was calculated from the ECG measurements by inverting each R-R interval.

FMRI data were pre-processed in SPM8 (http://www.fil.ion.ucl.ac.uk/spm). Motion correction was performed by registering each 3D volume to the first time point. Spatial smoothing was applied using a Gaussian kernel (FWHM ~ 4 mm) to enhance the signal-to-noise ratio. Following pre-processing three methods were used to extract cardiac induced signal fluctuation: (a) EMD was performed on each voxel time series, and the IMFs with instantaneous frequencies within the 0.8-1.1 Hz band were identified as cardiac related. (b) Signal from band-pass filtering at the same band, and (c) RETROICOR with 2nd order Fourier series fitting.

Time series in voxels which registered to large blood vessels and have high cardiac signal energy were taken and their time-frequency curve was then calculated using Hilbert transform. Results from each method were compared to the true heart rate curve.

Results and Discussion Results from one representative subject are shown below. The cardiac signals from major blood vessels and their energy distribution extracted by all three methods are shown in Figure 1 and 2, respectively. Figure 3 displays the smoothed time-frequency curves of the cardiac signal generated by four different methods: subject true heart rate from ECG measurement (red dashed), EMD (cyan), band-pass filtering (purple), and RETROICOR (green). The instantaneous frequency of the IMF matches very well with the real heart rate variation, while band-pass filtering and regression results doesn't present the same resemblance. As heart rate is often not stationary, it is expected that simple filtering will not generate a proper result. And although RETROICOR uses ECG data as correction template, errors in trigger detection, the limited number of Fourier fitting kernels, and regression on the global scale could all contribute to its deviation from real heart rate curve.

Conclusion We have demonstrated that EMD has the ability to identify BOLD signal components that closely correspond to the true cardiac activity. While the sampling rate of fMRI data is sufficient to avoid major aliasing of physiological noise and the target neuronal activity, EMD can serve as a model-free method to extract and remove these unwanted fluctuations without additional ECG measurements.

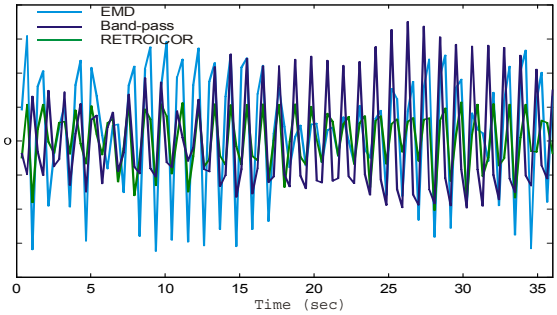

Figure 1 Cardiac signals extracted by EMD (cyan), band-pass filtering (purple), and RETROICOR (green).

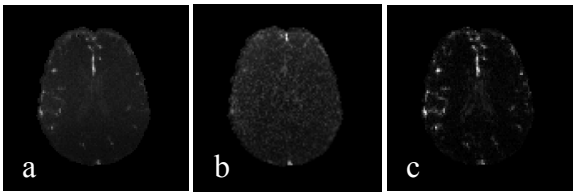

Figure 2 The energy distribution of signals extracted by: a) IMF, b) band-pass filtered signal of 0.8-1.1*Hz*, and c) RETROICOR.

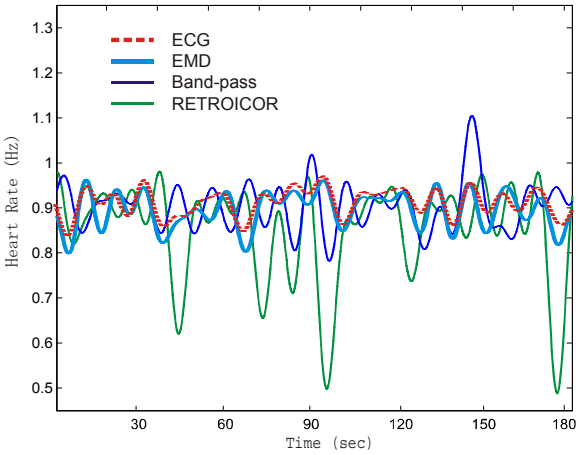

Figure 3 Smoothed time-frequency curves of the cardiac signal generated by four different methods: subject true heart rate from ECG measurement (red dashed), EMD (cyan), band-pass filtering (purple), and RETROICOR (green).

References

[1] Dagli et al., NeuroImage 9: 407–415 (1999); [2] Bhattacharyya *et al*., MRM 22: 9-13 (2004); [3] Cordes *et al*., AJNR Am. J. Neuroradiol. 22: 1326–1333 (2001); [4] Chuang and Chen, MRM 46: 344–353 (2001); [5] Beall *et al*., Neuroimage 37: 1286–1300 (2007); [6] Glover et al., MRM 44: 162-167 (2000); [7] Huang *et al*., Proc. R. Soc. London Ser. A 454: 903-995 (1998).