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Evoked hemodynamic response estimation using ensemble empirical mode decomposition based adaptive algorithm applied to dual channel functional near infrared spectroscopy (fNIRS)

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HIGHLIGHTS

- We describe a new method to improve evoked hemodynamic response estimation.
- EEMD decomposition and two different adaptive algorithms applied to dual channel fNIRS.
- fNIRS signals with non-stationary property of physiological components were simulated.
- The method does not require a prior assumption on the amplitude, shape and duration of the hemodynamic responses.
- The proposed method could outperform the other commonly used methods.

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ABSTRACT

Background: The quality of the functional near infrared spectroscopy (fNIRS) recordings is highly degraded by the presence of physiological interferences. It is crucial to efficiently separate the evoked hemodynamic responses (EHRs) from other background hemodynamic activities prior to any further processing.
New method: This paper presents a novel algorithm for physiological interferences reduction from the dual channel fNIRS measurements using ensemble empirical mode decomposition (EEMD) technique. The proposed algorithm is comprised of two main steps: (1) decomposing reference signal into its constituents called intrinsic mode functions (IMFs) and (2) adaptively defining appropriate weights of the corresponding IMFs to estimate the proportion of physiological interference in standard channel measurement.
Results: Performance of the proposed algorithm was evaluated using both synthetic and semi-real brain hemodynamic data based on four parameters of relative mean squared error (*rMSE*), Pearson's correlation coefficient (R^2), percentage estimation error of peak amplitude (E_{PA}) and peak latency (E_L).
Comparison with existing methods: Results obtained from synthetic data revealed that both the *EEMD based normalized least mean squares* (EEMD-NLMS) and *EEMD based recursive least squares* (EEMD-RLS) methods could reduce the average *rMSE* by at least 34% and 49%, respectively, when compared with widely used methods: *block averaging*, *band-pass filtering* and *principal and/or independent component analysis*. Furthermore, the two proposed methods outperform the *regression method* in reducing *rMSE* by at least 21% and 35% respectively when applied to semi-real data.
Conclusions: An effective algorithm for estimating the EHRs from raw fNIRS data was proposed in which no assumption about the amplitude, shape and duration of the responses is considered.

1. Introduction

Functional near infrared spectroscopy (fNIRS) is a new non-invasive neuroimaging technique that indirectly monitors brain activity by detecting associated changes in blood flow of cortical micro vasculatures (Nozawa and Kondo, 2009). When a given functionally localized part of the brain is stimulated by means of an

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appropriate visual, auditory, cognitive or motor task stimulus, the regional cerebral blood flow (rCBF) in the related region is increased. This is due to the phenomenon known as the neurovascular coupling. The variations in the amount and spatial distribution of blood flow are closely related to the changes in the neural activity through a complex sequence of coordinated events involving neurons, glia, and vascular cells (Pasley and Freeman, 2008). As such, fNIRS provides a suitable means for measuring and monitoring variations in the intensity of the light passing through the tissue which is typically within the wavelength range of 650–950 nm. The two main natural light absorbing chromophores within the tissue in this range are oxygenated hemoglobin (HbO_2) and deoxygenated hemoglobin (HbR). The variations in the concentration of these chromophores can be calculated using the modified Beer–Lambert law (MBLL). Functional near infrared spectroscopy is increasingly being used by neuroscientists due to its low cost, high temporal resolution, portability and quick setup as well as the ability to measure the time variations in both HbO_2 and HbR without imposing a major restriction to the subject.

In spite of these advantages, fNIRS is associated with certain shortcomings where the depth of penetration of light photons is limited and it is unable to measure cortical activity in deep brain layers. Furthermore, spatial resolution of fNIRS is also of limited value as compared with functional MRI. fNIRS measurements carries the effect of some of unrelated natural physiological based fluctuations. Sensitivity of the optical measurements to the evoked hemodynamic responses (EHRs) is degraded by the disturbances engendering from ongoing physiological activities (e.g., cardiac, respiratory, low and very low frequency oscillations) which occurs in the superficial layer of the scalp as well as in the brain tissue which are known as "systemic" or "global" interferences (Huppert et al., 2009; Obrig et al., 2000). The recorded signal is also very sensitive to the subject's head motion which is due to the imperfect optical coupling between the fNIRS optodes and the subject's head. Several algorithms have been previously developed to extract the true evoked hemodynamic responses from the noisy signals recorded by either single or dual and/or multi-channel fNIRS instruments. The most simple and commonly used technique for removing global interferences from the contaminated EHR signals is the block averaging (BA) technique. In this technique, true EHR is recovered by time domain averaging of N recorded responses to the N identical stimuli (Cutini et al., 2008; Taga et al., 2011). BA is based on the assumptions that (i) global interferences are independent from the evoked responses and (ii) there is a phase difference between physiological components from one stimulus to the other one. The main disadvantage of the BA method is that EHR cannot be estimated using a single or a small number of fNIRS recordings ($N > 50$). Bandpass filtering (BPF) has also been used to reduce the effect of the systemic artifacts from a single channel fNIRS recordings (Franceschini et al., 2003). In general, BPF can only be effective when the frequency contents of the desired signal and that of the interferences do not overlap, which is not the case with regards the fNIRS signals. In fact, the low frequency components of the artifacts (i.e. respiration and the Mayer wave) and the EHR signals are the same (≈0.2 Hz). Another approach for reduction of physiological interference from the fNIRS measurements has been developed using a dual channel fNIRS system (Gagnon et al., 2011; Saager and Berger, 2008; Umeyama and Yamada, 2009; Yamada et al., 2009; Zhang et al., 2007a,b, 2009). In this method, the channel with a small source–detector distance (<1 cm) is considered as the reference channel. Previous studies showed that the penetration depth of the NIR light within the brain tissue is about half of the source–detector distance (Gratton et al., 2000). Therefore, the signal of the reference channel is only sensitive to the hemodynamic fluctuations occurring within the superficial capillaries. The distance between the source and the detector of the second channel, which is considered as the standard channel, is usually larger (≈3 cm). Therefore, light can penetrate deeper to reach the cerebral cortex. Hence, the signal of the standard channel contains both evoked hemodynamic response and systemic interferences. The reference channel measurement and its step delayed signals were used as regression vector for reducing systemic interference, based on adaptive filtering adopted by Zhang et al. (2007a,b). Saager and Berger (2005) utilized a linear minimum mean squared estimator (LMMSE) to find appropriate scaling coefficients for the reference signal in order to subtract the scaled reference signal from the standard signal in order to remove interfering trends. Both principal component analysis (PCA) and independent component analysis (ICA) have been used to reduce the extra cerebral systemic interferences from the fNIRS signals (Kohno et al., 2007; Leung et al., 2005; Zhang et al., 2005). These methods are based on the fact that the spatial distribution of the EHR and the systemic interferences are different. While brain functional activity is highly localized, systemic interferences are generally global and their effects can be seen in all channel recordings (Gratton et al., 2005). In Franceschini et al. (2006), the N-channel recorded hemodynamic signals were decomposed into N uncorrelated components by means of PCA. Next, by replacing the first principal component by a value of zero, the interfering surface effects were reduced. In Virtanen et al. (2009), on the other hand, the N-channel recorded hemodynamic signals were decomposed into a maximum number of N independent components using ICA. A mixing matrix is then estimated by maximizing the statistical independency of the components. The spatial distributions of the independent components were then used to identify the superficial components. A coefficient of spatial uniformity (CSU) was introduced in Kohno et al. (2007) and the independent component with the largest CSU value was interpreted as the global interference. Next, by setting the corresponding columns of the mixing matrix, which are related to the independent component with the largest CSU, to zero the global interference were reduced. A main disadvantage of both PCA and ICA algorithms is that the noise intercrosses from noisy channels to all other channels making the amplitude of the EHRs to be under estimated.

Recently, Zhang et al. considered the empirical mode decomposition (EMD) technique as an effective tool for reducing the global interferences from the fNIRS signals (Zhang et al., 2010, 2011). Although it was shown that the EMD based method is very effective, but there are still some annoying problems to be solved. The main drawback of the EMD technique is the mode mixing phenomena that sometimes occur between the intrinsic mode functions (IMFs). Mode mixing can lead to aliasing in the time–frequency distribution of the signal, making it difficult to interpret the physical meaning of the individual IMFs. Due to this problem some references do not recommend to apply the EMD method in biomedical signal processing applications (Schlotthauer et al., 2010; Sweeney et al., 2012, 2013). To overcome the mode mixing problem of the EMD, two new modified EMD based algorithms were proposed which are namely the ensemble empirical mode decomposition (EEMD) (Wu and Huang, 2009) and the complete ensemble empirical mode decomposition with adaptive noise (CEEMDAN) (Torres et al., 2011).

In this study, we employed the EEMD algorithm to decompose the reference signal of a dual channel fNIRS instrument into its IMFs each with distinct frequency content. Next, a set of appropriate weights for different mode functions are calculated using the two conventional adaptive methods of the normalized least mean squares (NLMS) and the recursive least squares (RLS). The true EHR is estimated by minimizing the squared error between the output of the adaptive filter and the standard channel measurement. In order to compare the performance of the proposed algorithms to that of other commonly used methods, the four parameters of