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Review

Quantitative evaluation of deep and shallow tissue layers' contribution to fNIRS signal using multi-distance optodes and independent component analysis

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ABSTRACT

To quantify the effect of absorption changes in the deep tissue (cerebral) and shallow tissue (scalp, skin) layers on functional near-infrared spectroscopy (fNIRS) signals, a method using multi-distance (MD) optodes and independent component analysis (ICA), referred to as the MD-ICA method, is proposed. In previous studies, when the signal from the shallow tissue layer (shallow signal) needs to be eliminated, it was often assumed that the shallow signal had no correlation with the signal from the deep tissue layer (deep signal). In this study, no relationship between the waveforms of deep and shallow signals is assumed, and instead, it is assumed that both signals are linear combinations of multiple signal sources, which allows the inclusion of a "shared component" (such as systemic signals) that is contained in both layers. The method also assumes that the partial optical path length of the shallow layer does not change, whereas that of the deep layer linearly increases along with the increase of the source–detector (S–D) distance. Deep- and shallow-layer contribution ratios of each independent component (IC) are calculated using the dependence of the weight of each IC on the S–D distance. Reconstruction of deep- and shallow-layer signals are performed by the sum of ICs weighted by the deep and shallow contribution ratio. Experimental validation of the principle of this technique was conducted using a dynamic phantom with two absorbing layers. Results showed that our method is effective for evaluating deep-layer contributions even if there are high correlations between deep and shallow signals. Next, we applied the method to fNIRS signals obtained on a human head with 5-, 15-, and 30-mm S–D distances during a verbal fluency task, a verbal working memory task (prefrontal area), a finger tapping task (motor area), and a tetrametric visual checker-board task (occipital area) and then estimated the deep-layer contribution ratio. To evaluate the signal separation performance of our method, we used the correlation coefficients of a laser-Doppler flowmetry (LDF) signal and a nearest 5-mm S–D distance channel signal with the shallow signal. We demonstrated that the shallow signals have a higher temporal correlation with the LDF signals and with the 5-mm S–D distance channel than the deep signals. These results show the MD-ICA method can discriminate between deep and shallow signals.

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Introduction

Functional near-infrared spectroscopy (fNIRS) measures the changes in brain haemodynamics and oxygenation; indeed that encompasses cerebral blood volume (CBV) but is not restricted to that. The measurement of them by fNIRS is performed by radiating weak visible or near-infrared light into the head and detecting the back (scattered) reflected light from another position (Chance et al., 1993; Hoshi and Tamura, 1993; Jöbsis, 1977; Kato et al., 1993; Villringer et al., 1993). A fNIRS imaging system, such as optical topography, that uses multiple light sources and detectors (Koizumi et al., 1999; Maki et al., 1995; Yamashita et al., 1996) is used to obtain two-dimensional topographical images of the changes in brain haemodynamics and oxygenation. The fNIRS systems have been widely used for research (Minagawa-Kawai et al., 2002; Obata et al., 2003; Sato et al., 1999) and clinical purposes (Suto et al., 2004; Watanabe et al., 1998), especially for measuring the brain activity of infants and children (Grossmann and Johnson, 2010; Homae et al., 2010; Minagawa-Kawai et al., 2009; Nakano et al., 2009; Taga et al., 2000, 2003), because they have a high level of safety (Ito et al., 2000; Kiguchi et al., 2007) and require few constraints.

The effects of scalp blood volume on fNIRS signals have been reported in many previous studies (Germon et al., 1998; Kohno et al., 2007; Kohri et al., 2002; Minati et al., 2011; Smielewski et al., 1997; Takahashi et al., 2011), and artifacts on NIRS signals induced by changes to head inclination have been reported (Durduran et al., 2009). It has been reported that some individual variability in correlation between fNIRS signal and scalp blood flow or mean blood pressure (Tachtsidis et al., 2008a) and that the systemic changes that also affect extracranial signals can lead to false positives in fNIRS signals (Tachtsidis et al., 2009). It has also been reported that regional cerebral oxygen saturation is affected by extracranial contamination (Davie and Grocott, 2012; Sørensen et al., 2012). It is therefore a pressing issue to quantify the effect of extracerebral blood on fNIRS signals and to discriminate between the effects of intra- and extracerebral tissue.

In an attempt to address this issue, several methods have been used with source–detector (S–D) pairs of a normal distance (e.g., 30 mm). For example, signal discrimination using independent component analysis (ICA) (Akgül et al., 2006; Katura et al., 2008; Kohno et al., 2007; Markham et al., 2009; Patel et al., 2011), principal component analysis (PCA) (Virtanen et al., 2009; Zhang et al., 2005), and model-based analysis such as the general linear model (GLM) (Cui et al., 2011; Plichta et al., 2007) have been applied to fNIRS signals. A method for extracting task-related components by maximizing inter-block covariances (Tanaka et al., 2013) has been reported. Yamada et al. (2012) proposed a method for separating functional and systemic signal based on a negative or positive linear relationship between oxygenated (oxy-Hb) and deoxygenated (deoxy-Hb) changes. Furthermore, time-resolved spectroscopy (TRS) measurements have been proposed for extracting extracerebral signals using early (superficial) and late (deep) photons (Aletti et al., 2012) or using moments of the distributions of times of flight of photons (Liebert et al., 2004, 2012).

With multi-distance probes, diffuse optical tomography (DOT) has also been studied for its potential to improve spatial resolution (Boas et al., 2004; Dehghani et al., 2009; Gregg et al., 2010; Heiskala et al., 2012; Shimokawa et al., 2012; Zeff et al., 2007). In this technique, the reconstruction of a three-dimensional image of brain activities during visual stimulation has been achieved with continuous wave (CW) light sources. However, sources and detectors with a high density arrangement are necessary, and these studies were mainly applied for the occipital region (Dehghani et al., 2009; Gregg et al., 2010; Heiskala et al., 2012; Zeff et al., 2007). Because the forehead, over the prefrontal cortex, has no hair and the effect of scalp blood current has been reported to be significant (Kirilina et al., 2012; Takahashi et al., 2011), a detailed investigation into the application of DOT to the prefrontal cortex, including modeling of the human head, needs to be performed.

With fewer multiple-distance optodes, inter-channel subtraction methods have been reported as methods for eliminating surface-layer effects, where the signal of a short S–D distance channel is multiplied by a proper value (i.e., scaling factor) to be subtracted from that of a long-distance channel. Such methods are often used in conjunction with static linear-regression (Luu and Chau, 2009; Saager and Berger, 2005; Saager et al., 2011; Toronov et al., 2001), adaptive filtering (Zhang et al., 2007a, 2007b, 2009), and Kalman filtering (Gagnon et al., 2011). However, it has been reported that if there is a correlation between the deep and shallow signals, the deep signal might be over-subtracted by the short-distance regressor with a subtraction method (Kirilina et al., 2012). To obtain the scaling factor, the ratio of partial path lengths for the multiple S–D distances is necessary. Umeyama and Yamada (2009) and Yamada et al. (2009) proposed a multiple-distance method using partial optical path lengths calculated by a Monte Carlo simulation. Fabbri et al. (2004) reported that NIRS signal changes obtained during a 30-s baseline acquisition are mainly caused by absorption changes in the superficial, extracerebral tissue, and the scaling factor can be acquired by calculating the ratio of absorbances obtained at multiple S–D distances under such a baseline condition. In this calibration method, however, only extracerebral tissue blood volume should be modulated whereas cerebral blood volume should be stopped, which is very difficult because it has not been established how to stop or prevent the change of cerebral blood volume even during a short period of time.

It has been reported that the heterogeneity of shallow blood volume change is derived from extracerebral and extracranial veins such as pial veins, supraorbital veins, frontal (supratrochlear) veins, and superficial

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