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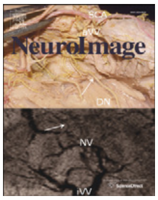

Reducing motion artifacts for long-term clinical NIRS monitoring using collodion-fixed prism-based optical fibers

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ABSTRACT

As the applications of near-infrared spectroscopy (NIRS) continue to broaden and long-term clinical monitoring becomes more common, minimizing signal artifacts due to patient movement becomes more pressing. This is particularly true in applications where clinically and physiologically interesting events are intrinsically linked to patient movement, as is the case in the study of epileptic seizures. In this study, we apply an approach common in the application of EEG electrodes to the application of specialized NIRS optical fibers. The method provides improved optode-scalp coupling through the use of miniaturized optical fiber tips fixed to the scalp using collodion, a clinical adhesive. We investigate and quantify the performance of this new method in minimizing motion artifacts in healthy subjects, and apply the technique to allow continuous NIRS monitoring throughout epileptic seizures in two epileptic in-patients. Using collodion-fixed fibers reduces the percent signal change of motion artifacts by 90% and increases the SNR by 6 and 3 fold at 690 and 830 nm wavelengths respectively when compared to a standard Velcro-based array of optical fibers. The SNR has also increased by 2 fold during rest conditions without motion with the new probe design because of better light coupling between the fiber and scalp. The change in both HbO and HbR during motion artifacts is found to be statistically lower for the collodion-fixed fiber probe. The collodion-fixed optical fiber approach has also allowed us to obtain good quality NIRS recording of three epileptic seizures in two patients despite excessive motion in each case.

Introduction

Near-infra red spectroscopy (NIRS) uses changes in the intensity of near-infrared light measured between source and detector optical fibers ('optodes') positioned on the head to infer changes in hemoglobin concentrations in the cerebral cortex. The technique was first described by Jobsis (1977) and is increasingly used as a practical and inexpensive approach to investigating brain function in both clinical and research environments. NIRS has been used in a broad range of studies of healthy brain function (Homae et al., 2011; Lloyd-Fox et al., 2010; Obrig et al., 2002; White and Culver, 2010) and a wide spectrum of neurological diseases (Hock et al., 1996; Okada et al., 1994; Sakatani et al., 1999; Vernieri et al., 1999; Watanabe et al., 2002) (for a review: Irani et al., 2007).

One of the challenges of the application of NIRS is the occurrence of movement-induced artifacts. The NIRS signal is susceptible to motion artifacts because of relative movement between an optical fiber and the scalp. Optical contact can be temporarily or permanently altered due to this relative movement, which often occurs if the subject moves their head or face (Sweeney et al., 2011). Changes in optical contact result in pronounced artifact in the NIRS signal, and the amplitude of these motion artifacts is generally an order of magnitude larger than any underlying hemodynamic variations. This makes it very challenging to recover the actual physiological NIRS signal when measurement is contaminated by motion artifacts (Cooper et al., 2012a).

A major advantage of NIRS over techniques such as fMRI or PET is that NIRS is portable, and is therefore easily applied to vulnerable subject groups, such as infants, children or patients with neurological conditions. However, these groups are also much more likely to exhibit frequent movement and therefore produce motion artifacts. Epilepsy is one area of NIRS research that shows a lot of potential, as NIRS is one of the few techniques that can be used continuously and safely throughout epileptic seizures themselves. NIRS has been used in multiple studies of seizures in both infants and adults (Cooper et al., 2011; Gallagher et al., 2008; Roche-Labarbe et al., 2008; Watanabe et al., 2002), and recent advances in data

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acquisition, processing and interpretation of NIRS data are likely to allow whole-head imaging of the hemodynamic and metabolic changes occurring in the cerebral cortex during seizures in the near future (Cooper et al., 2012b; Franceschini et al., 2006; Koch et al., 2010; Lareau et al., 2011; Takeuchi et al., 2009). However, epileptic seizures routinely involve excessive and often violent convulsions and movement of the head, and motion artifacts present a major obstacle to obtaining meaningful neurophysiological information about epileptic seizures.

Motion artifacts can be identified after measurements have been obtained, and there are various motion artifact removal techniques that can be applied to the signal (Robertson et al., 2010; Cooper et al., 2012b). There are fundamentally two approaches to the minimization of motion artifacts: methods which require some external measurement of the movements of the subject (such as adaptive filtering (Robertson et al., 2010; Zhang et al., 2007)) and methods that do not require extra measurements (such as principal component analysis, Kalman filtering, wavelet based filtering and spline interpolation (Izzetoglu et al., 2010; Molavi and Dumont, 2012; Scholkmann et al., 2010; Zhang et al., 2005)).

Methods of the first category use a measurement that is highly correlated to subject motion (such as an accelerometer signal) to inform a filtering algorithm of NIRS components that are likely to be artifacts, which allows their removal in post-processing. The second category of motion artifact removal techniques uses some inherent characteristic of motion artifacts to remove them from the data. Applying principal component analysis (Zhang et al., 2005), for example, relies on the assumption that motion artifacts provide a great majority of the variance of a given NIRS signal and that motion artifacts are apparent in multiple channels. Wavelet based filtering (Molavi and Dumont, 2012) transforms the data into the wavelet domain and assumes that the outlying wavelet coefficients will be due to motion artifacts and these are removed from the data prior to performing the inverse wavelet transform.

Although these motion correction methods have been shown to be very effective in improving motion-contaminated data (Cooper et al., 2012b), they cannot be as effective as simply avoiding the motion artifact in the first place. Because motion artifacts are due to relative motion between an optode and the scalp, providing stronger and more robust optode-scalp coupling can greatly improve the quality of NIRS data. Different techniques of applying optodes to head have been developed in order to optimize the NIRS signal with respect to factors such as hair, skin color, and fiber stability (Strangman et al., 2002). For example, brush optodes have been designed that improve the optical signal by threading through the hair (Khan et al., 2012). Another approach is to use a mechanical mounting structure to carry the weight of the optodes (Coyle et al., 2007; Giacometti and Diamond, 2013). Modified cycle helmets, thermoplastic molded to the contours of each subject's head, spring-loaded fibers attached to semi-rigid plastic forms and fibers embedded in rubber forms are other alternative approaches of applying optodes to head (Lloyd-Fox et al., 2010; Strangman et al., 2002). In this study, we introduce a new way of applying NIRS optodes to the scalp which will reduce motion artifact contamination, as well as allow better optode-scalp contact and fiber stability against head. This will facilitate the use of NIRS in population groups where motion artifact contamination of the data is more likely. With this motivation, we designed a miniaturized optode, which allows the optical fiber tip to be fixed on the head using the same clinical adhesive that is commonly used to apply EEG electrodes for long term monitoring of epilepsy patients. We compare the efficacy of the new collodion-fixed fiber probe with a standard Velcro-based probe in a study of healthy subjects who simulated motions that capture the types of motions during a seizure. The new probe method was also applied to epilepsy in-patients in a clinical setting to allow long-term simultaneous NIRS and EEG monitoring. This study provided a further assessment of the utility of the new probe as it allowed us to obtain measurements of cerebral hemodynamics during seizures despite significant motion of the patient in each case.

Methods

We have designed a miniaturized optical fiber tip (Fig. 1) which consists of a glass prism (CASMED, Connecticut), a mirrored surface and a prism-housing that holds the prism and connects it to the optical fiber. The small size and low profile of this design mean that it can be coupled to the head using a clinical adhesive (Collodion, Mavidon, FL), which is commonly used to apply EEG electrodes to the scalp. The application process is as follows. A towel is placed around the subject's shoulders in order to protect their clothing from the glue. The hair is parted using a cotton-tipped stick. A square of collodion-impregnated gauze (2–3 cm) is placed on the scalp as to cover the optode. The collodion is dried using compressed air.

Motion artifact study

To provide a quantified assessment of the efficacy of the collodion-fixed optical fibers, we performed a study which applied both collodion-fixed and standard optical fiber probes to healthy subjects. Five healthy adult subjects were recruited for this study (1 female, 4 male). The subjects were 23–52 years old (mean 35 ± 13). The study was approved by Massachusetts General Hospital and each subject gave informed written consent.

Data were collected using a TechEn CW6 system operating at 690 and 830 nm (TechEn, Inc., MA, USA). The standard Velcro-based NIRS probe contained 2 sources and 4 detectors and was located over the right motor region of each subject. The collodion-fixed fibers were attached over the left hemisphere of the subject so as to symmetrically match the standard probe (Fig. 2). Figs. 2 and 3 are obtained using Atlasviewer, part of the HOMER2 NIRS processing package (Huppert et al., 2009). The 3D positions of the sources and detectors are obtained using a 3D digitizer (Polhemus Inc., VT). During recording, subjects were asked to perform seven different types of movement in order to induce motion artifacts mimicking normal motions as well as motions seen during seizure: reading aloud, nodding their head up and down, nodding sideways, twisting right, twisting left, shaking head rapidly from side to side and raising their eyebrows. The Psychophysics toolbox for MATLAB (Brainard, 1997) was used to control the timing of the experiment. Each motion trial was performed for 3 s and trials were repeated 5 times for each motion type with a randomized inter-trial interval of between 5 and 10 s. This resulted in a 6 minute-long recording period. Following this, we acquired 12 min of resting state data, with the same probe arrangement.

Epilepsy study

As part of an ongoing clinical study, we have begun to apply collodion-fixed optical fibers to epilepsy in-patients. The subjects were recruited from the in-patients of the Epilepsy Monitoring Unit of Massachusetts General Hospital (Table 1). The Massachusetts General Hospital Institutional Review Board approved the study and all subjects gave informed written consent which included the application of collodion. Our optical probes were fixed to the head at the same time as the clinical EEG electrodes so as to minimize the impact of our study to the standard clinical procedure.

The positioning of the optical probes was decided based on the medical history of patient, so as to maximize the likelihood that NIRS measurements would be sensitive to the epileptic focus (Fig. 3). The EEG electrodes are placed according to the clinically standard International 10–20 system (XLTEK, a division of Natus, Ontario, Canada). The optical fibers used in this study were ~11 m in length, allowing the subjects to move comfortably about their room and use the restroom.