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A portable high-density absolute-measure NIRS imager for detecting prefrontal lobe activity under fatigue driving

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ABSTRACT

Driving fatigue is one of the primary causes of traffic accidents nowadays. It is thus imperative to develop a technique to monitor levels of driving fatigue. The emergent near-infrared spectroscopy (NIRS) is now capable of measuring functional cerebral activities noninvasively and sensitively in terms of hemodynamic responses, shedding light on the possibility to detect signals regarding fatigue-specified cerebral activities. This work innovatively developed a NIRS device aimed at fatigue detection of drivers, and the device was designed to be portable so that it can be easily operated during driving. Moreover, the device is absolute-measure so that the data can be compared among drivers. The probe is high-density and we can visualize brain functional responses after imaging. The high sensitivity, stability, and reliabilities of our device were fully tested in the order of ink experiment, cuff experiment, and on-human test. For the in-situation on-human test, we recruited 3 taxi drivers and collected data by our device during 8 h' driving. It's found that the hemodynamics-represented cerebral activation decreased with driving duration, which indicated our device's strong potential in monitoring fatigue.

1. Introduction

Due to drivers' lacking in vigilance and wariness during driving, the society has witnessed a growing proportion of traffic accidents caused by driving fatigue. Therefore, driving fatigue has become one of the leading causes of tragedies on road. Serious results may arise from a dearth of perceptiveness of potential accidents, the absence of recognition of traffic conditions, and the disability to control vehicles [1,2]. Such exhibitions of mental and physical inattentiveness of drivers pose a devastating threat to the lives of drivers as well as other people engaged in traffic [1,2], and distinguish themselves as one of the most dangerous causes for security-related public issues, as evidenced by recent statistical results [3].

Since fatigue driving, along with drunk driving, have long been the most severe traffic problems concerning public security, years of attempts on signal detection for both cases have existed. For drunk driving, people have employed different approaches to detect, control and prevent it for decades, such as alcohol sensors, STM32-based devices with brain wave signals collected, analog and digital integrated circuit modules and so on. As for fatigue driving, in comparison, approaches like Electro-encephalogram (EEG) and Electro-oculogram (EOG) have brought about progresses [12,13], and symptoms such as eye fatigue features have also been used as medium through which detection of signals involved can be performed [14]. What's more, different algorithms and regression models have been explored to evaluate the effectiveness of such techniques in determining the level of driving fatigue or vigilance, and assessing the deviation of such fatigue results from reality. For example, the SEM (slow eye movements) detection algorithm first introduced by Magosso et al. [10] is now used in the realm of EOG detection of driving fatigue [21]. GELM (graph regularized extreme learning machine) model and SVM (support vector machine) model have been used in assessing the level of driving fatigue [13]. As can be seen from results by previous researchers, techniques for detecting driving fatigue are already in relatively good maturity and precision.

However, the existing varieties of well-developed detection methods for driving fatigue still suffer from a number of restrictions. Therefore, they need revisions and supplementations in order to further improve the precision and timeliness. EEG signals collected is easily affected by movements from the eyes or other body parts [12], and thus for better precision of the experiment, the designer has to set various restrictions. Participants engaged in the experiments using EEG signals are often required to remain in alertness and concentrate only on driving [22]. What's more, EEG signals are also easily affected by noise. EOG only

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detects eye movements, so it gets rid of some of the problems of EEG, and has worked well by adopting a fusion of the two techniques [13]. The analyses of EOG techniques require information concerning the movement of the human eyes, such as blinks, eyelid movements, rapid eye movements (REM) and slow eye movements (SEM). Such signals could be used for extracting information regarding the level of fatigue, but the information only accounts for a certain aspect of the fatigue level of the human body [13]. This calls for further revisions in them, and it would be better if an alternative approach could be developed which is capable of improving or supplementing existing techniques.

At the time when the need for an alternative driving fatigue detector is emerging, a portable high-density near-infrared spectroscopy (NIRS) technology has come out, with the ability to continuously determine the absolute concentration of oxygenated and deoxygenated hemoglobin noninvasively. NIRS detectors are able to get rid of the drawbacks of EEG and EOG in terms of flexibility, for its results are immune to movements of body parts. What's more, other advantages such as noninvasiveness and portability make it special among fatigue detection techniques, because such properties make it applicable for in-situation on-road applications. Another advantage of this technology is its ability to achieve absolute measurements, as illustrated in a previous work [6]. After obtaining the absolute results in the forms of oxygenation parameters, it is easier for us to compare results among various subjects, and thus allow for overall evaluations for levels of driving fatigue and, if further applied in the medical field, assist in determining the causes for diseases in the population. More importantly, setting up absolute standards in driving fatigue becomes easier. With devices capable of measuring absolute values, it is probable in the future that numerical boundaries for determining driving fatigue could be legalized, and just as drunk driving, regulations and laws related to driving fatigue can finally be firmly implemented. Such advantages of the NIRS technique make it a good alternative and even stand out among techniques for detecting driving techniques in the future.

The technique has been developed for in vivo measurements for different parts of the human body [4], including legs, breast, and functional brain activities. Specifically, for measurements related to brain activities, previous studies have experimented on NIRS devices for the feasibility of light stimulation and treatments in brain-related diseases. For example, the study carried out in [5] shows the results of penetration depth of photons by using Monte Carlo simulations and high precision VCH (Visible Chinese Head) model. For this work, we are innovatively using NIRS for the purpose of detecting driving fatigue and visual attention during prolonged driving [19,20], by looking at the prefrontal lobe activities of the drivers under test.

Using such a portable high-density near-infrared spectroscopy (NIRS) imager, a serial of experiments was carried out to test its sensitivity, stability, and reliability. Preliminary experiments, including ink experiment and cuff experiment, were designed for the purpose of testing the device's stability and sensitivity. We obtained results which provided us with information concerning the performance of the device for different wavelengths of near-infrared light (NIR), and different distances from the detector to the LED light source. After that came the on-human in-situation experiment for testing the reliability of the device, which was carried out on three drivers during an eight-hour period on a working day. In particular, we tested the device's performance on detecting drivers' attention variation adjusted by fatigue due to prolonged driving, and obtained the cerebral image of hemoglobin distribution by using the techniques adopted in [5]. The results of the experiments showed consistency and reliability of our device, and substantiate the feasibility and effectiveness of the device in its function of fatigue detection. Our device, using NIRS bearing the advantages of noninvasiveness, flexibility, effectiveness and absolute measurements, is expected to have great potential for future applications on detection of driving fatigue. If being integrated with wireless communication hardware and protocols in the future, we believe the device would be widely used for on-road real-time detection of driving fatigue, and ensure order and safety in a world with better traffic and less accidents.

2. Methods

2.1. NIRS theory

The two forms of hemoglobin in the human body, oxygenated hemoglobin (HbO_2) and deoxygenated hemoglobin (Hb), transform into each other as the level of oxygen in the tissue changes. Generally, if the tissue is rich in oxygen, Hb transforms into HbO_2, resulting in a increasing concentration of HbO_2 and a decreasing concentration of Hb. This suggests an increasing level of oxygenation in the tissue. Everything holds vice versa.

Nowadays, multiples NIRS techniques have been developed, and one of the most prevalent approaches involves the detection of near-infrared light (NIR) intensity changes and quantification of oxygenation changes in blood, including the changes of HbO_2 and Hb [4]. The function between light intensity and oxygenation of the blood, that is, the function between light intensity and concentration of HbO_2 and Hb, has been elaborated in [4], in which experiments have been carried out to determine the optimal selection for extinction coefficients in the function. Such work ensures an accurate function between the light intensity and concentrations of HbO_2 and Hb, and therefore guarantees that the results calculated from the collected data by the accurate. These theories have formed the foundation for the algorithms used in our data processing on computer.

For incident Near Infrared Light (NIR), Hb absorbs the wavelength range 650–800 nm more than other wavelengths, while HbO_2 absorbs wavelength range 800–1000 nm more. For our work, we use 735-nm wavelength integral light source to detect the changes of concentration of Hb, and 850-nm wavelength integral light source to detect the changes of concentration of HbO_2 [5,6]. Simultaneously, due to similar absorptivity between HbO_2 and Hb at 805 nm, we use this wavelength to detect total changes of the blood volume. Since the level of oxygenation is widely used in NIRS technology, and it represents the level of tissue fatigue [11], we used this parameter in our experiments, and we believe it acts as a good starting point towards future driver's fatigue detection applications.

2.2. Device

We designed a portable high-density absolute-measure NIRS device to detect driver fatigue, and the light emitters as well as detection probes embedded into the surface of the device panel were carefully allocated and designated in a particular spatial manner, as shown in Fig. 1(a). LED1 and LED2 are two multi-wavelength near-infrared light sources (735/805/850 nm), serving to provide human tissues with different wavelengths of near-infrared light so that concentrations of both $HbO_2$and Hb could be detected and measured. D1-D12 are detectors, serving to receive the light with different wavelengths reflected and scattered from human tissues, and transmit the optical information for analyzing and processing. The distance between LED1 to LED2 is 4.5 cm, and the distances between each detector to the nearest LED are 2.8–3.5 cm, in a similar manner to the reference [8], forming a dense spatial arrangement of the emitters and detectors on the probe panel. In the experiments, light received by detectors from light sources other than the LEDs was considered interferences, and light data received by the further LED is trivial (such as LED1 light reaching D9–D12), because we prefer local concentration, and light information coming from the nearer LED is more accurate in determining the local concentration. The device probe is connected with the computer (PC) with a cable, as shown in Fig. 1(b). Fig. 1(c) it shows the subject doing the experiment on the computer. When the detectors receive the optical signals from human tissues, they transmit the signals into the computer for further analyses, and the final results are absolute values of concentrations of HbO_2 and Hb, as well as the pseudo-color imaging of the results [7].