EEG-fNIRS Study of Cerebral Hemodynamic Fluctuations

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Abstract: This study demonstrates that very low-frequency hemodynamic fluctuations, detectable by fNIRS and processed by CWT, appear around seizure onset, identified by EEG. These changes originate from cerebral tissue and may improve seizure detection and localization of the seizure onset zone in patients with drug-resistant epilepsy.

Keywords: Neural Codes, Neuroimaging, fNIRS, Epilepsy, cerebral hemodynamic

Introduction

In recent years, functional near-infrared spectroscopy (fNIRS) has emerged as a promising non-invasive neuroimaging modality capable of complementing electrophysiological recordings of patients with epilepsy [1]. fNIRS uses near-infrared light to measure changes in the concentration of oxygenated (HbO) and deoxygenated (HbR) hemoglobin in cortical tissues. It can infer localized changes in cerebral blood oxygenation with a spatial resolution of approximately 1-3 cm and a temporal resolution around 0.1sec (10Hz). These measurements reflect the physiological response of blood vessels to neuronal activity through neurovascular coupling. Consequently, fNIRS provides an indirect, yet robust, measure of neural activation, particularly suited for continuous monitoring over long periods in naturalistic environments.

Despite its advantages, traditional analyses of fNIRS data does not normally capture slow and subtle fluctuations in hemodynamics (mostly due to short recordings durations), and are commonly removed by high-pass filtering. Continuous Wavelet Transform (CWT) [2] that enables the decomposition of fNIRS signals into their constituent frequency components as a function of time, is well-suited to identify non-stationary and very low-frequency hemodynamic fluctuations.

In this study, we combine fNIRS with either non-invasive scalp video-encephalography (VEEG) or invasive stereo-EEG (SEEG) to continuously monitor patients with focal epilepsy over several hours. We apply CWT to fNIRS data to detect very low-frequency hemodynamic changes around seizure onset. We hypothesize that these changes are spatially and temporally aligned with the seizure-onset-zone (SOZ) and may serve as biomarkers for early seizure prediction and improved localization in patients with focal drug-resistant epilepsy (DRE).

Methods

Six adult patients with focal epilepsy undergoing long-term EEG monitoring (VEEG or SEEG) were included in the analysis (out of 11 recruited patients), following approval by the ethics committee at Hadassah Medical Center and signing an informed consent form. Simultaneous fNIRS and EEG recordings were performed, capturing 14-92 hours of data per patient. Standard fNIRS emitter- and detector-coupled optical fibers were positioned at a 3cm separation, with at least one pair positioned at a 1-1.5cm separation (comprising a short channel for capturing superficial contributions). Detected signals at each wavelength were preprocessed to extract changes in oxyhemoglobin (HbO) and deoxyhemoglobin (HbR) concentrations using the modified Beer Lambert law. CWT was applied to 4 hours recording sections (at 5-10Hz) using the Morse wavelet in MATLAB. For each patient, all electrographic seizures were identified based on VEEG or SEEG recordings by expert clinicians. Data was then cropped 30 minutes prior and following each seizure, and all the CWT scalograms for each 60 minutes sessions were aligned relative to the seizure onset and then averaged. Power distribution over time and frequency was extracted, and for each frequency bin, the time period where the power exceeded the mean power for longer than 5 seconds, was identified. Within this time period, the time point of the maximal power (TMP) and the time point of the center of gravity (CG) of the power distribution were calculated.

Results

An example of an average-CWT scalogram for two fNIRS channels from the same patient is presented in Fig. 1. The dashed red line (time =0) is the seizure onset time, as was identified from the SEEG signals. On the left panel, a standard fNIRS channel (with a 3cm emitter-detector separation (EDS)) overlaying the suspected SOZ is presented. On the right panel a short fNIRS channel (with a 1cm EDS) is presented. High power blobs (yellow colors) that indicate higher than average fluctuations at relatively low frequency bins (0.002-0.02Hz) are clearly evident in the left panel, but are hardly present in the right one. This indicates that for the large EDS channel, very low-frequency fluctuations that originate from the cerebral micro-vasculature surrounding the SOZ are detectable by CWT. However, they are not evident in hemodynamic fluctuations within extracerebral layers that are picked up by the short channel.

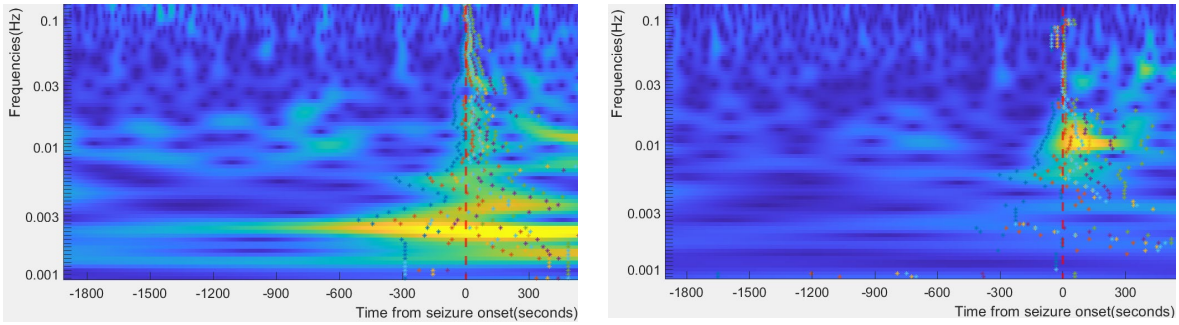

Figure 1: CWT representation of change in HbO around a seizure for patient #9. Dashed red line marks seizure onset (t=0). Colored dots indicate some parameters, like TMP and CG that were calculated for each frequency bin but are not discussed herein.

Similar data was visually analyzed for all other patients, and in some cases was lateralized to the region overlaying the SOZ identified by other imaging studies.

Discussion

This study demonstrates the manifestation of cerebral hemodynamic fluctuations at very low frequencies (0.002-0.02 Hz) using fNIRS and CWT during epileptic seizures. These very-slow fluctuations in cerebral blood oxygenation appear before (and after) electrographic activity in all patients. Additionally, such changes were absent in short-channel fNIRS recordings, indicating a cerebral, rather than extracranial or motion related, origin.

CWT enabled the detection of these slow, non-stationary signals, which are typically missed by standard bandpass analysis methods. The ability to capture early vascular changes suggests these signals may reflect upstream processes in ictogenesis.

Conclusions

Clinically, the described approach offers a promising, non-invasive tool for seizure detection and improved SOZ localization. Its portability, low cost, and compatibility with long-term monitoring make it particularly suited for integration into closed-loop neuromodulation systems. As such, fNIRS-CWT could become a valuable adjunct tool in the workup of patients with DRE who are candidates for further interventions.

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References

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