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Application of Near-infrared Spectroscopy in Human Elite Freedivers while Deepdiving on a Single Breath Hold

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Abstract: Near-infrared spectroscopy was used to observe the cerebral hemodynamic response of freedivers during single breath-hold training dives. We observed variability in hemodynamic progression, and heartbeat shape changes with diving depth.

1. Introduction

More user-friendly devices and improved portability have increased interest in near-infrared spectroscopy (NIRS), including in research settings where non-invasive access to cerebral hemodynamics was previously not possible. These changes now allow NIRS applications in more natural and more extreme environments. Studying the brain in different environments can expose vital clues to better understand blood perfusion control and gas exchange in the brain. Humans voluntarily expose themselves to extreme physiological conditions, be it professionally or recreationally, that affect the perfusion of the brain. Yet such effects on the brain are not well understood due to a lack of adaptation of suitable non-invasive measurement devices. Here we explore the influence of prolonged breath-holds on the brains of human competitive freedivers during deep training sessions. The extreme conditions these freediving individuals are exposed to include rapid changes in hydrostatic pressure, temperature, exercise, and asphyxia. Freediving is therefore associated with a risk of hypoxic syncope, which can be fatal. This may be especially prominent during ascent from deep dives, where gas exchange may be compromised, though a direct observation of the hemodynamic response under developing extreme hypoxia has never been recorded. Using a continuous wave NIRS system, we measured 17 dives as deep as 107 m, lasting up to 4 minutes on a single breath, in 5 volunteers. We identified different types of hemodynamic responses to the dive condition and observed changes in the cerebral blood volume cardiac pulse waveform as a function of diving depth and heart rate.

2. Methods

Measuring cerebral hemodynamic changes in freediving humans and marine mammals requires the adaptation of NIRS instruments to the harsh environments of the sea, including challenges such as the potential of electrical short-circuiting through saltwater, high hydrostatic pressure, limits on instrument size and material, as well as data transfer restrictions. These must be addressed while still ensuring comfort and biocompatibility for the divers.

We adapted a continuous wave NIRS system (PortaLite mini, Artinis, Medical Systems BV, Netherlands) operating at two wavelengths around 750 nm and 850 nm, to measure the hemodynamic changes in human freediver’s frontal cortex. The system operates with 3 light sources, placed respectively 30 mm, 35 mm, and 40 mm from a common detector. This NIRS sensor was refitted to the environmental conditions of the marine environment and renamed PortaDiver. The PortaDiver’s light emitting diodes and photodiode were fitted in a custom opaque polyoxymethylene housing placed in a silicone mold; the housing was then filled with epoxy to create a water-resistant encasing of the optical hardware, while ensuring the external surface of the diodes and photodiodes were not covered, to maintain optical integrity. The light sources and receivers were potted in clear, flexible polyurethane to create a comfortable connection to the skin, able to follow the participant’s head contour. The sensor head was connected via cable to a water-sealed box encasing the recording device, which was controlled via a Bluetooth connection and could be activated by a magnetic key from the outside. Given data storage capacity limitations, the device recorded at 10 Hz.

In addition to optical measurements, a biologging device (Little Leonardo W1000-PD3GT, Little Leonardo, Tokyo, Japan) was deployed. It recorded tri-axial acceleration (32 Hz), diving depth (1 Hz) and environmental temperature (1 Hz) during the dive.

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2.2 Human freediver measurements

From a cohort of 5 elite competitive freedivers, 17 deep freedives, each performed on a single breath were recorded during training in the open sea, spanning 8 constant-weight (CWT), 4 constant weight no fins, and 5 free immersion dives (FIM) [1]. After giving informed consent, the divers were equipped with the PortaDiver and Little Leonardo. The divers then performed a freedive at their own pace, including a pre-dive respiratory maneuver to fill the lungs above their normal total capacity, known as “lung packing” [2].

2.3 Signal processing

Light intensity changes were then converted into changes in oxygenated (ΔHbO) and deoxygenated (ΔHb) hemoglobin using the modified Beer-Lambert’s law [3]. From the multi-distance measurements, the tissue oxygen saturation index (TSI) was calculated using spatially resolved spectroscopy (SRS) [4]. We further extracted the heart rate (HR) from the NIRS signal, using the HR derivation algorithm presented in [5]. Arterial oxygen saturation (SpO_2) was estimated by calculating the pulsatility ratio of ΔHbO to ΔtHb (ΔtHb = ΔHbO + ΔHb). The pulsatility was defined as the power spectral density extracted from a spectrogram at the HR for ΔHbO and ΔHb. We extracted the cardiac waveform shape of ΔtHb, which was associated with blood volume changes, through a custom peak-finding algorithm. A window of -0.5 to 2.9 seconds around each identified pulse onset was extracted. SNR was improved by computing a moving average across 15 consecutive pulses. A z-score rejection was applied to remove outlier waves that differed from the average by more than 3 standard deviations over the duration of the pulse. For direct shape comparison, we normalized the cardiac pulses in length and height between 0 and 1.

3. Results

Two examples of responses to freediving are shown in Fig.1, for two different diving depths and movement patterns of the divers. ‘Lung packing’ appears to have caused a reduction in ΔHbO with a consequent fall in ΔtHb and TSI, before the onset of diving (Fig. 1C&D).

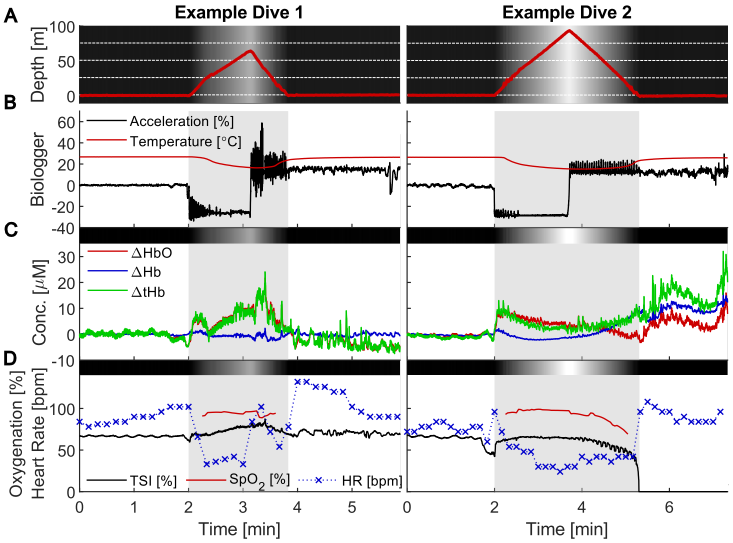

Fig. 1. Two example dives to 67 m (CWT) and 97 m (FIM) depth from two freedivers, showing (A) diving depth with color bar corresponding to the depth, (B) ambient temperature and accelerometer reading, (C) cerebral hemodynamic responses, (D) cerebral tissue and arterial blood oxygen saturation, and heart rate changes. High-frequency peaks and troughs in the accelerometry signal are indicative of leg movements associated with swimming in the dive 1 and arm movements of pulling along the rope in dive 2. Figure after [6].

Upon diving ΔHbO and ΔtHb rose to exceed pre-diving levels and a restoration of TSI to pre-lung packing levels. Across the remainder of diving, patterns of change in ΔHbO and ΔHb varied across dives and divers, which could be due to differences between individuals, diving depths, durations, and disciplines. In example dive one, cerebral hemodynamic changes resulted in TSI remaining close or above pre-diving levels throughout the dive. In example dive 2, however, while TSI remained high throughout the descent phase of the dive, during ascent TSI dropped and showed a noticeable increase in the rate of decline in the last 10-15 m as ΔHb and ΔtHb rose. This phenomenon of low TSI, concomitant with increased ΔtHb engendered by rising ΔHb, was seen in 8 of the 17 dives logged – all of which were the deepest and longest dives performed by participants.

The cardiac response to the dive, determined by pulse shape and pulse rate extraction from the hemodynamic signal, shows strong variability (see Fig. 2). The heart rate was coupled with exercise, which was most profound at the beginning of the decent swimming to overcome buoyancy and the beginning of the ascent to overcome negative buoyancy, as shown by the acceleration data in Fig. 1B. During the free fall section of the decent [1], heart rates slowed significantly, showing the typical diving response [1,6] with the longest inter-beat interval observed across all dives measuring 5.4 seconds. The cardiac waveform changed from a typical percussion wave dominated shape (Fig. 2, left side) to a bi-phasic shape with a dominant tidal wave as observed in humans with increased intracranial pressure (Fig. 2 during maximum diving depth). Waveforms normalized in length and height emphasize this trend and show a relationship to heart rate and diving depth.

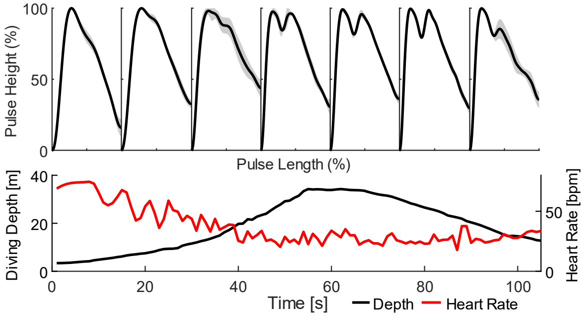

Fig. 2. Average heart beats in ΔtHb are calculated based on one example dive. The widths of the top graphs correspond to the duration in the bottom graph time axis over which heart beats were averaged (15 s). The shaded area shows the standard deviation. Figure after [6].

4. Discussion

We demonstrate that NIRS can be adapted to harsh environmental conditions, allowing us to improve the understanding of hemodynamic response of humans in extreme freediving. In our analysis we made two major discoveries: 1) variability in hemodynamic responses between different dives, and 2) the cardiac pulse waveform changes during the dive, which may indicate extreme changes to the pressure dynamics governing cerebral blood flow. While some diver's hemodynamic response maintained cerebral oxygenation, others were exposed to pronounced cerebral hypoxia, especially during the last 10 m of ascent, in some dives. This is potentially caused by deeper and longer dives. Further investigation into the variability of hemodynamic responses could lead to a better understanding of human freediving physiology, including the mechanisms underlying hypoxic syncope [5]. The change in cardiac waveform experienced over the course of the dive appeared to be associated with heart rate and diving depth. The increase of the second peak in the cardiac wave, the tidal wave, is associated with an increase in arterial compliance, as often seen in individuals with increased intracranial pressure or highly elevated systolic blood pressure. The intracranial pressure might be associated with the increase in hydrostatic pressure acting on the freediver's body. Furthermore, substantially decreased vessel compliance as a result of peripheral vasoconstriction to support deep and prolonged freedives might, despite the profound bradycardia, cause an increase in systolic pressure [7].

Understanding the challenges to the cardiovascular system and the consequences for brain oxygenation in freedivers might improve our understanding of the effects of repeated short-term hypoxemia and cerebral hyperperfusion in other clinical settings. Further investigation with breath-holding volunteers on land will help distinguishing specific freediving from breath-holding hemodynamics. Comparisons to marine mammals and their unique adaptation to the sea will shed further light on the hemodynamic conditions revealed here.

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