

TITLE PAGE

Citation Format: C. Caredda, L. Contini, B. Montcel, R. Re, "Study of the effect of breathing exercises on cerebral and extracerebral hemodynamics with TD-fNIRS," in 4th Translational Biophotonics: Diagnostics and Therapeutics, 1393435 (2025). ISBN: 9781510698055. European Conference on Biomedical Optics 2025 (ECBO), 22-26 June 2025.

Copyright notice: Copyright 2025 Society of Photo-Optical Instrumentation Engineers. One print or electronic copy may be made for personal use only. Systematic reproduction and distribution, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper are prohibited.

DOI Abstract link:

<https://doi.org/10.1117/12.3097799>

Study of the effect of breathing exercises on cerebral and extra-cerebral hemodynamics with TD-fNIRS

Charly Caredda,^{1,*} Letizia Contini,² Bruno Montcel¹ and Rebecca Re^{2,3}

¹ Univ Lyon, INSA-Lyon, Université Claude Bernard Lyon 1, UJM-Saint Etienne, CNRS, Inserm, CREATIS UMR 5220, U1294, F69100, Lyon, France

² Dipartimento di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milan, Italy

³ Istituto di Fotonica e Nanotecnologie, Consiglio Nazionale delle Ricerche, Piazza L. da Vinci 32, Milan, Italy

*charly.caredda@creatis.insa-lyon.fr

Abstract: In this study, we analyzed the relationship between physiological and time-domain (TD) functional near infrared spectroscopy (fNIRS) signals during breathing exercises. Results showed a synchronization between cardiovascular and respiratory systems during modulated breathing exercises. We also observed a strong coherence between cerebral TD-NIRS signals and peripheral blood volume changes during breath holding tasks which could indicate a mediation of the autonomic nervous system.
© 2025 The Author(s)

1. INTRODUCTION

Even at rest, the brain exhibits spontaneous hemodynamic oscillations, reflecting the underlying mechanisms of autoregulation, neurovascular coupling and cardiorespiratory interactions. These oscillations can be investigated with functional near infrared spectroscopy (fNIRS) [1]. Using time domain (TD) fNIRS, it is possible to measure cerebral oscillations at a suitable acquisition rate (up to 20 Hz) [2, 3] and to separate the signal contribution from the cerebral and extra-cerebral layers. At rest, respiratory conditions can have an impact on hemodynamic signals, which could lead to reduced sensitivity in fNIRS studies [4, 5]. However, questions remain about how breathing strategies influence brain perfusion. The aim of this work is to study the link between physiological signals (respiratory rhythm and peripheral blood volume changes) and cerebral and extra-cerebral hemodynamic oscillations during breathing exercises (free, modulated, restrictive breathing and breath holding tasks). A time-frequency analysis was conducted to evaluate the instantaneous phase difference and the instantaneous synchronisation of phase and change in power between TD-NIRS and physiological signals.

2. MATERIAL AND METHODS

The measurements were conducted at the Physics department of Politecnico di Milano, on a healthy subject, who voluntarily took part in this study. Acquisitions were performed on the right prefrontal cortex with a TD-NIRS device, using a source-detector distance of 4 cm and a sampling frequency of 20 Hz. A detailed description and characterization of the device used to acquire the data can be found in Re et al., *Sensors*, 2023 [2].

During the measurements, the subject was lying on a bed with a 30° tilted backrest and was asked to relax with closed eyes for the entire measurement session. In addition to TD-NIRS data, physiological signals (peripheral blood volume changes and respiratory rhythm) were collected at 256 Hz during the breathing exercises. Seven sessions of 400 s were acquired for one subject:

1. Free breathing: the subject was asked to relax completely, breathing freely
2. Modulated breathing at normal breathing rate: a metronome was used to guide the respiration, imposing a normal respiratory volume with a breathing rate of 0.183 Hz
3. Modulated breathing at slow breathing rate: a metronome is used to guide the respiration, imposing a breathing rate of 0.083 Hz. This rate was selected to induce an increase of breathing volume with respect to normal ventilation
4. Free restricted breathing: the subject breathed through a mask with a circular hole of 10 mm diameter
5. Modulated restricted breathing at normal breathing rate (10 mm mask)

6. Modulated restricted breathing at normal breathing rate (4.5 mm mask)
7. Breath holding tasks: the session consisted in 12 epochs of 34 s decomposed in four steps: 2 s: the subject took air with a deep breath, 15 s: the subject hold breath, 2 s: the subject breathed out, 15 s: the subject breathed freely

TD-NIRS data were analyzed to extract the time series of oxygenated and deoxygenated hemoglobin concentrations (C_{HbO_2} and C_{Hb} in M) using the Mean Partial Pathlength method, assuming the probed tissue as represented by a bilayer model with a 1 cm-thick superficial (extra-cerebral) layer [6]. With this technique, cerebral and extra-cerebral time series of hemoglobin concentration can be obtained with a sampling frequency of 20 Hz. We evaluated the effects of the different measurement conditions on the hemodynamics of the probed tissues with wavelet semblance and coherence analyses [7]. Semblance and coherence indexes have been calculated between TD-NIRS and physiological signals (respiratory rhythm and peripheral blood volume changes). The semblance and coherence quantifies the instantaneous phase difference and the instantaneous synchronisation of phase and change in power between two time series in the time-frequency domain, respectively. The significant threshold in wavelet analyses was calculated with Monte Carlo simulations at 5% statistical significance. Wavelet data collected during free, modulated and restrictive breathing were averaged over the time dimension in order to calculate frequency dependent indexes. For data collected during breath holding tasks, two sets of data were created by averaging wavelet data along the time dimension during breath hold and free breathing periods.

3. RESULTS AND DISCUSSION

In Fig. 1 (a, b, c, d), we plotted the coherence indexes calculated between cerebral and extra-cerebral hemodynamics and the respiratory rhythm. In graphs (e, f, g, h), we represented the coherence indexes calculated between cerebral and extra-cerebral hemodynamics and the peripheral blood volume changes. Colored areas indicated frequency bands of interest: endothelial (magenta), nitric oxide (NO) related-endothelial (blue), neurogenic (green), respiratory (blue) and cardiac (red) bands. In the graphs (a, b, c, d), the grey areas indicate frequencies that are neglected because they correspond to frequencies below the respiratory frequency measured with the respiratory belt.

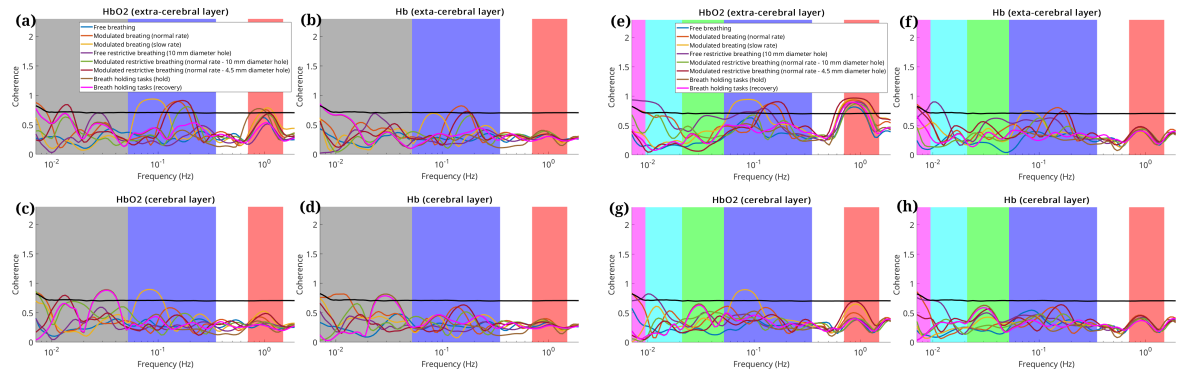


Fig. 1. Coherence indexes calculated during breathing exercises. (a, b, c, d) - Indexes calculated between respiratory rhythm and C_{Hb} , C_{HbO_2} time courses. (e, f, g, h) - Indexes calculated between blood volume pressure rhythm and C_{Hb} , C_{HbO_2} time courses. Solid lines represent the mean indexes, and the colored areas indicated frequency bands of interest: endothelial (magenta), nitric oxide-related endothelial (blue), neurogenic (green), respiratory (blue) and cardiac (red) bands. The black lines indicate the significant threshold. In graphs, Six frequency areas were identified.

In the cardiac frequency band (red area), there is a strong coherence between extra-cerebral C_{HbO_2} and the respiratory rhythm during modulated breathing exercises and breath hold, see graph (a). This could be due to the intermittent detection of the cardiac pulsation by the respiratory belt. This could also indicate a synchronization between the extra-cerebral cardiovascular and respiratory systems, which refers to the cardiorespiratory coupling [8]. As expected, there is a strong coherence between extra-cerebral C_{HbO_2} and peripheral blood volume changes during all breathing exercises, see graph (e). We can also observe a strong coherence between cerebral C_{HbO_2} and peripheral blood volume changes for slow modulated breathing exercises and the most restrictive breathing exercise, see graph (g).

In the respiratory frequency band (blue area), there is a strong coherence between extra-cerebral TD-NIRS signals (C_{HbO_2} and C_{Hb}) and the respiratory rhythm when the subject performed modulated restrictive breathing exercises, see graphs (a) and (b). We also observe strong coherence with cerebral C_{HbO_2} signals when the subject performed slow modulated breathing, see graph (c). We assume that this is due to a large inhaled air volume. Coherence is higher when measured with C_{HbO_2} signals than with C_{Hb} signals, which might indicate that peripheral blood volume changes is highly saturated in O_2 . We also observe strong coherence in the cerebral layer for C_{HbO_2} for slow modulated breathing, see graph (g). The strong coherence between TD-NIRS signals and peripheral blood volume changes during modulated breathing exercises may be due to the cardiorespiratory coupling [8].

In the neurogenic frequency band (green area), we do not observe significant coherence indexes between TD-NIRS signals and peripheral blood volume changes. However, we observe strong coherence in the extra-cerebral layer during the free restrictive breathing exercise (see graphs (e) and (f)) and in the cerebral layer during the recovery and breath-holding periods of the breath-holding task (see graphs (g) and (h)). This seems to indicate that breath-holding tasks can lead to fluctuations in peripheral and cerebral hemodynamics that could be mediated by the autonomic nervous system during breath-holding (sympathetic nervous system) and recovering periods (parasympathetic nervous system). Additionally, previous research has shown that breath-holding in elite apneists triggers significant sympathetically-mediated peripheral vasoconstriction [9]. While our study focuses on a non-elite apneist, our findings are consistent with these observations.

For the NO-related endothelial and endothelial-related frequency bands, significant coherence was observed for free restrictive breathing. However, these indexes must be taken with caution because most of the data used to calculate the indexes were outside the wavelet cone of influence.

4. CONCLUSIONS

In this work, we analyzed the relationship between physiological signals and TD-NIRS during breathing exercises. Results showed a synchronization between cardiovascular and respiratory systems during modulated breathing exercises. We also observed a strong coherence of cerebral TD-NIRS signals and peripheral blood volume changes during breath holding tasks which could indicate a mediation of the autonomic nervous system during breath-holding tasks. In a future study, we plan to perform a measurement campaign with several subjects.

Acknowledgments

This work was supported by Laserlab-Europe EU-H2020 871124 project; Labex Primes (ANR-11-LABX-0063/ANR-11-IDEX-0007); Infrastructures d'Avenir en Biologie Santé (ANR-11-INBS-000); France Life Imaging (ANR-11-INBS-0006).

References

1. Hellmuth Obrig et al. Spontaneous low frequency oscillations of cerebral hemodynamics and metabolism in human adults. *Neuroimage*, 12(6):623–639, 2000.
2. Rebecca Re et al. Reliable fast (20 hz) acquisition rate by a td fnirs device: brain resting-state oscillation studies. *Sensors*, 23(1):196, 2022.
3. Letizia Contini et al. Detectability of hemodynamic oscillations in cerebral cortex through functional near-infrared spectroscopy: a simulation study. *Neurophotonics*, 11(3):035001–035001, 2024.
4. Felix Scholkmann et al. Systemic physiology augmented functional near-infrared spectroscopy: a powerful approach to study the embodied human brain. *Neurophotonics*, 9(3):030801, 2022.
5. S. Guglielmini et al. Hemodynamics and vascular oxygenation measured at the forehead during changes in respiration: A spa-fnirs study. *Respiratory Physiology & Neurobiology*, 331:104364, 2025.
6. L. Zucchelli et al. Method for the discrimination of superficial and deep absorption variations by time domain fnirs. *Biomedical optics express*, 4(12):2893–2910, 2013.
7. A. Grinsted et al. Application of the cross wavelet transform and wavelet coherence to geophysical time series. *Non-linear processes in geophysics*, 11(5/6):561–566, 2004.
8. T. E. Dick et al. Cardiorespiratory coupling: Common rhythms in cardiac, sympathetic, and respiratory activities. *Progress in brain research*, 209:191–205, 2014.
9. Anthony R. Bain et al. Physiology of static breath holding in elite apneists. *Experimental Physiology*, 103(5):635–651, 2018.