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Exploring Nonlinear Heart Rate Variability for Assessing the Autonomic Nervous System in Hyperbaric Environments

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***Abstract*—Underwater diving presents noteworthy physiological challenges, impacting the autonomic nervous system (ANS) balance. Heart Rate Variability (HRV) is a widely used tool for ANS assessment. While standard HRV methods are prevalent in diving research, nonlinear HRV methods are still not fully exploited. In this study, we characterized cardiac variability complexity in hyperbaric environments using nonlinear methods. We recorded ECG signals from 31 subjects in a dry hyperbaric chamber across different pressure stages. Significant changes were noted between baseline and return-to-surface conditions. The observed differences suggest that the inclusion of these parameters in standard HRV analysis could help in a better understanding of diving physiology and serve as a potential diagnostic marker for associated risks.**

***Index Terms*—Diving, Autonomic Nervous System, Heart Rate Variability, Hyperbaric.**

I. Introduction

Underwater diving represents a considerable physiological challenge. Hydrostatic pressure, which increases with depth, and the presence of gases that can form bubbles during ascent, are critical factors that can trigger lethal responses in the diver's body to maintain homeostasis, expressed in the autonomic nervous system (ANS) through the balance between its sympathetic and parasympathetic branches. Monitoring the ANS response provides a deeper understanding of diving physiology and it serves as a possible diagnostic marker for associated risks [1]. Heart rate variability (HRV) is one of the most widespread tools for the non-invasive assessment of the ANS [2]. The relationship between changes in standard time and frequency domain HRV parameters and parasympathetic and sympathetic nervous system activity has been well established. Nonlinear methods appeared to extend the description regarding the complexity of mechanisms underlying HRV [3]. In recent years, the use of standard HRV features in diving medicine and releated research has gained popularity; however, there are few studies where nonlinear methods, in conjunction with the linear ones, have been utilized [4]. In this study, we have characterized the underlying complexity of cardiac variability in hyperbaric environments by using nonlinear methods with the aim of adding value to previous studies and extend the understanding of the human body's adaptation to these challenging environments.

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II. Materials and methods

A. Database Description

A total of 31 subjects were enrolled in this study. All subjects signed the written informed consent approved by "Comité de ética de la investigación con medicamentos de la inspección general de sanidad de la Defensa". The protocol consisted of simulating the hyperbaric environment of diving by using a dry hyperbaric chamber. Subjects experimented five different pressure stages at 1 atm (sea level (0i)), 3 atm (simulating 20 metres depth (20i)) and 5 atm (simulating 40 meters depth (40)), followed by a return to 3 atm (20s) and 1 atm (0s), where "i" means *immersion* and "s" means *surfacing*. Baseline corresponds to stage 0i. Throughout these stages, there were 5 min stops where the subjects remained in silence and without any movements.
Recordings were performed using a Nautilus device [5], which recorded the electrocardiogram (ECG) signal with three frontal bipolar leads at a sampling frequency of 2000 Hz.

B. Nonlinear Heart Rate Variability Analysis

Heartbeat time ocurrences were detected by using a wavelet-based single-lead automatic system [6]. Beat to beat (RR) time series were computed and ectopics and misdetections were corrected [7]. While time-frequency analysis of cardiac variability is performed from the HRV signal, for nonlinear analysis the RR series is used directly. Indices based on chaos theory such as correlation dimension D_2, sample entropy $SampEn$, approximate entropy $ApEn$, $ApEn_{max}$ and multidimensional approximate entropy $MApEn$ and indices $SD1$ and $SD2$ based on Pointcaré Plot were evaluated [8]. A 4 minute RR time series was considered for the indices computation. A Wilcoxon signed rank test for zero median was used to compare each stage to baseline. As the main objective is to check the nonlinear index variations with respect to the baseline condition, no multiple comparison test was performed.

III. Results

The results are related to 28 subjects instead of 31 due to bad signal quality. Figure 1 summarizes the nonlinear HRV indices calculated at the five different pressure stages described in section II which reported statistical significance in at least one of the comparisons with respect to baseline stage. Regardign this, all nonlinear indices showed in Figure 1 were found statistically increased values at 20s with respect to 0i. Furthermore, all calculated parameters showed a slight increase in their median compared to the baseline (0i) at the end of the protocol (0s). This increase was statistically significant only for SD_1 and SD_2, which exhibited similar change throughout the rest of the protocol stages. Both SD_1 and SD_2, along with the variables obtained from entropy analysis, except for $MApEn$, showed a significant increase compared to the baseline state upon returning to 3 atm (20s).

IV. Discussion and Conclusion

Hyperbaric environment has been previously reported to increase the parasympathetic activity of divers by time and frequency HRV analysis [9]. These changes in the ANS adaptation were also manifested by nonlinear indices as the ones presented in this work. A decrease in nonlinear indices has been related to an increase in the sympathetic activity comparing supine versus standing position [10]. Therefore, the observed increase in the different calculated entropy points to an increment of parasympathetic activity and in the complexity of cardiac variability adaptation.

The nonlinear characterization of the ANS in response to pressure changes highlights ANS hyperbaric environments adaptation. These results could provide a better understanding of the ANS behaviour under challenging conditions and improve safety protocols during diving.

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References

[1] A. Hernando, H. Posada-Quintero, M. Peláez-Coca, E. Gil, and K. Chon, "Autonomic nervous system characterization in hyperbaric environments considering respiratory component and non-linear analysis of heart rate variability." *Computer Methods and Programs in Biomedicine*, vol. 214, p. 106527, 2022.

[2] S. Akselrod, D. Gordon, F. A. Ubel, D. C. Shannon, A. C. Berger, and R. J. Cohen, "Power spectrum analysis of heart rate fluctuation: A quantitative probe of beat-to-beat cardiovascular control." *Science*, vol. 213, no. 4504, pp. 220–222, 1981.

[3] R. Sassi, S. Cerutti, F. Lombardi, M. Malik, H. V. Huikuri, C.-K. Peng, G. Schmidt, Y. Yamamoto, D. Reviewers:, B. Gorenek, G. Y. Lip, G. Grassi, G. Kudaiberdieva, J. P. Fisher, M. Zabel, and R. Macfadyen, "Advances in heart rate variability signal analysis: joint position statement by the e-cardiology esc working group and the european heart rhythm association co-endorsed by the asia pacific heart rhythm society," *EP Europace*, vol. 17, no. 9, pp. 1341–1353, 2015.

[4] R. Lundell and T. Ojanen, "A systematic review of hrv during diving in very cold water." *International Journal Of Circumpolar Health*, vol. 82, no. 1, 2023.

[5] D. Sokas, M. Gailius, and V. Marozas, "Diver physiology monitor and its graphical user interface." *Virt. Inst. Biomed.*, vol. 2, pp. 5–9, 2016.

[6] J. Martinez, R. Almeida, S. Olmos, A. Rocha, and P. Laguna, "A wavelet-based ecg delineator: evaluation on standard databases," *IEEE Transactions on Biomedical Engineering*, vol. 51, no. 4, pp. 570–581, 2004.

[7] J. Mateo and P. Laguna, "Analysis of Heart Rate Variability in the Presence of Ectopic Beats Using the Heart Timing Signal," *IEEE Trans. Biomed. Eng.*, vol. 50, no. 3, pp. 334–343, 2003.

[8] J. Bolea, R. Bailón, and E. Pueyo, "On the standardization of approximate entropy: Multidimensional approximate entropy index evaluated on short-term hrv time series," *Complexity*, vol. 2018, p. 15, 2018.

[9] M. D. Peláez-Coca, A. Hernando, M. T. Lozano, J. Bolea, D. Izquierdo, and C. Sánchez, "Heart rate variability to automatically identify hyperbaric states considering respiratory component," *Sensors*, vol. 24, no. 2, 2024. [Online]. Available: https://www.mdpi.com/1424-8220/24/2/447

[10] J. Bolea, E. Pueyo, M. Orini, and R. Bailón, "Influence of heart rate in nonlinear hrv indices as sampling rate effect evaluated on supine and standing," *Frontiers in Physiology*, vol. 7, 2016.

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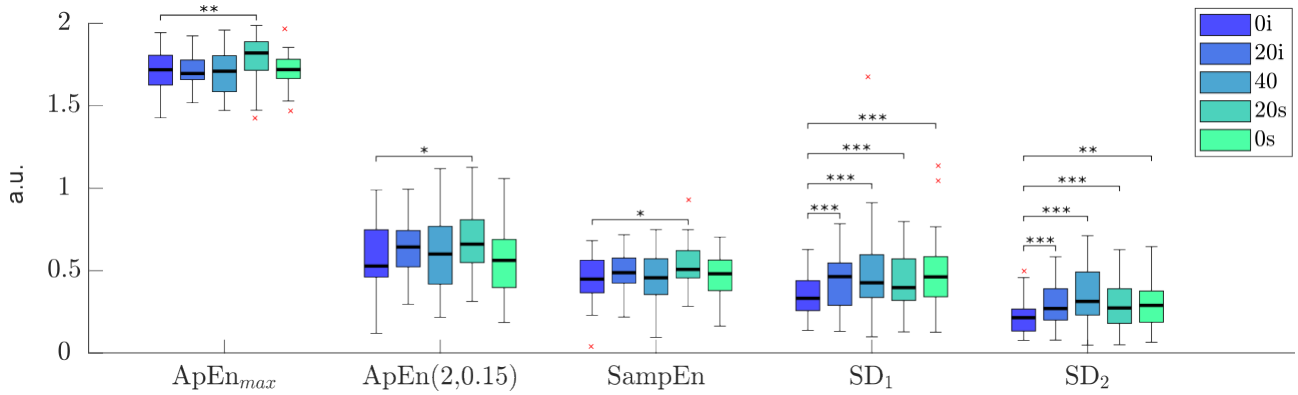

Fig. 1. Boxplots of nonlinear HRV indices with statistical significance when comparing to baseline condition. A Wilcoxon signed rank test was used. P-value is denoted as follows: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).