Autonomic Nervous System Response During Scuba Diving Activity

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Abstract

In this work, Heart Rate Variability indices are computed to analyze the Autonomic Nervous System response during a scuba diving activity. To do that, electrocardiogram signals from 6 subjects were recorded in a reservoir immersion. Two different stages were analyzed: baseline stage, where subjects remained seated outside the water; and immersion stage, where subjects performed physical activity in a non-controlled environment. The smoothed pseudo Wigner-Ville distribution was used for the time-frequency analysis. Results show a statistically significant increase of the mean heart rate and a significant decrease in the root mean square of the successive normal beats during the immersion stage. However, frequency-domain parameters did not show any significant difference between stages. Whereas time-domain parameters reflect a sympathetic activation during the immersion, caused by the predominance of the physical activity and the stress of the challenging environment, frequency-domain parameters are not able to capture it. Further studies are needed to draw more robust conclusions by increasing the number of subjects and exploring alternative methods to compute the Autonomic Nervous System frequency content.

1. Introduction

Diving is a challenging activity, where there is an increase in hydrostatic pressure proportional to depth (a descent of 10 meters implies a pressure increase of one atmosphere, atm). The immersion has an impact on the diver's body generating an internal response to maintain homeostasis. This response is reflected in the Autonomic Nervous System (ANS) through the balance between its two branches (sympathetic and parasympathetic or vagal). The most common non-invasive technique to measure ANS activity is the analysis of Heart Rate Variability (HRV), extracted from the electrocardiogram (ECG).

The ANS response has been analyzed in several works inside a hyperbaric chamber, which allows an increase of pressure in controlled conditions without going under the water. The results of these studies suggested a reduction in the heart rate and an increase in parasympathetic activity [1–3]. There are only a few studies analyzing ANS response during real immersions and they also show dominance of the parasympathetic activity [4–6]. However, these studies involved lower depths in a pool [5], or they analyzed divers that remained static during the immersion [4].

In this work, a new database with experienced divers performing physical tasks inside the water and surrounded by a challenging non-controlled environment with low visibility is used. A study of the ANS response during this immersion is done in order to see if there is a predominance of the sympathetic activity because of the stress associated to the environment, or a predominance of the vagal activity due to the immersion, or an activation of both branches. To do that, time-domain parameters from the RR series and frequency-domain parameters using the smoothed pseudo Wigner-Ville distribution (SPWVD) are analyzed to see if they could characterize the fast response of the ANS to immersion changes.

2. Materials

ECG from 6 experienced SCUBA divers from a diving unit of the Spanish Army (all men), with a mean age of 30.8 ± 5.9 years, were registered in a real dive in a reservoir, with the approval of the ethics committee "Comité de ética de la investigación con medicamentos de la in-

spección general de sanidad de la Defensa". Two different stages were analyzed. In the baseline stage, divers remained seated comfortably in silence and without performing movements during 5 minutes outside the water. In the immersion stage, divers performed a real immersion (between 15 and 25 m of maximum depth, 49 to 82 ft) breathing air, developing physical tasks inside the water and surrounded by a challenging environment with low visibility. Three minutes at the maximum depth during the immersion were selected for the analysis of this stage.

Recordings were performed using a Nautilus device [7], which allows the ECG signal to be recorded with three leads at a sampling frequency (fs) of 2000 Hz, along with the atmospheric pressure (fs=250 Hz).

3.   Methods

3.1.   ECG Analysis

A low-pass FIR filter was applied to the ECG signal to remove the baseline interference (cut-off frequency of 0.03 Hz) [8]. Heartbeats were detected using a wavelet-based algorithm over the second lead of the recorded ECG signal [9]. Ectopic beats and missed and false detections were identified and corrected [10]. As a result, the QRS complexes could be located in the ECG, and the difference between consecutive R waves was used to generate the RR time series. Then, the time-varying integral pulse frequency modulation model was applied to determine the influence of the ANS on the beat occurrence time series [11]. Using this model, the instantaneous heart rate signal (HR) was created at a sampling rate of 4 Hz.

The mean heart rate (HRM) was obtained by low-pass filtering HR with a cut-off frequency of 0.03 Hz. The heart rate variability signal (HRV) was calculated as the subtraction of these two terms: $HRV = HR - HRM$.

3.2.   Time-Domain Parameters

In addition to the HRM, measured in beats per minute (bpm), three more time-domain parameters could be computed from the beat-to-beat time series [12], obtaining one value per stage as the mean of the 3 or 5 minute-stage-duration:
• $SDNN(s)$: Standard deviation of the Normal-to-Normal (NN) intervals, as a measure of statistical dispersion. This parameter could be interpreted as an indicator of overall ANS activity.
• $RMSSD(s)$: Square root of the mean of the squares of the successive differences between adjacent NN intervals. This parameter mainly reflects the parasympathetic tone.
• $pNN50(\%)$: Number of pairs of successive NNs that differ by more than 50 ms, divided by the total number of NN intervals.

3.3.   Frequency-Domain parameters

Time-frequency analysis was applied to HRV to characterize the fast response of the ANS to the immersion. The SPWVD was selected to perform this analysis because it provides better resolution than non-parametric linear methods, independent control of time and frequency filtering, and power estimates with lower variance than parametric methods when rapid changes occur. To attenuate the interference terms, time and frequency smoothing windows were chosen to be Hamming windows of length 2N-1 = 203 and 2K+1 = 513 samples, respectively [13].

Two main components were considered: a low-frequency (LF) component, which reflects both sympathetic and parasympathetic activity, and a high-frequency (HF) component, which reflects only parasympathetic activity. As it is well known, parasympathetic component is related to respiratory sinus arrhythmia, so in this work HF band is centred in the respiratory rate, Fr [13]. Respiratory rate was extracted from the ECG, from QRS slopes and R-wave angle [14]. HF bandwidth is 0.125 Hz, in order to have a similar bandwidth with respect to the LF band. For the 6 subjects, the lower limit of HF band was always above 0.15 Hz (no overlapping with the LF band).

Four frequency-domain indices are computed during the entire stage, and then one value is given:
• $PLF(a.u.)$: Mean of the power in the LF band [0.04 - 0.15 Hz], in arbitrary units.
• $PHF(a.u.)$: Mean of the power in the HF band [Fr-0.0625 - Fr+0.0625], in arbitrary units.
• $PLFn(n.u.)$: Mean of the instantaneous power in the LF band over the sum of the instantaneous powers of both LF and HF bands. $PLFn = PLF/(PLF + PHF)$, in normalized units.
• $R_{LF/HF}(ad)$: Mean of the ratio between the instantaneous power in the LF band and the instantaneous power in the HF band. $R_{LF/HF} = PLF/PHF$, adimensional.

Figure 1 shows an example of two time-frequency maps for the same subject, one per stage.

3.4.   Statistical analysis

Finally, a statistical analysis was performed to compare baseline stage versus immersion stage. First, a Shapiro-Wilk test was applied to verify whether data distribution is normal. Then, as these distributions were no-normal, the Wilcoxon paired test was applied, with a p-value$\leq$0.05 to define the significance.

4.   Results

Figure 2 presents the results of time-domain and frequency-domain parameters from baseline and immersion stages during the reservoir immersion. On the one
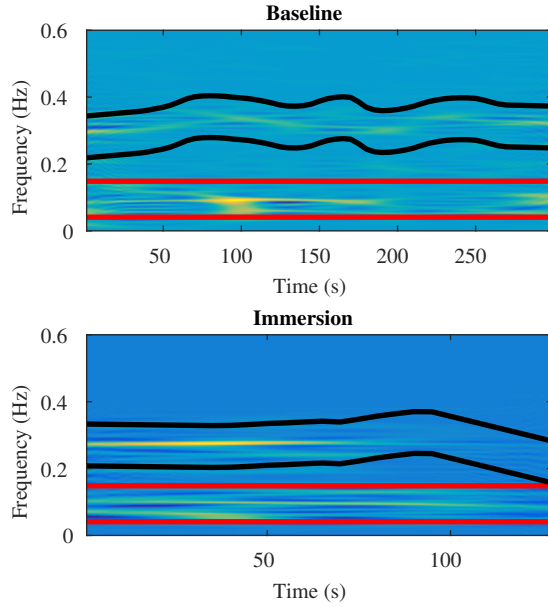
Figure 1. Time-frequency maps for baseline and immersion stages, with the LF band delimited in red and the HF band delimited in black.

hand, time-domain parameters show that HRM significantly increases and $RMSSD$ decreases during the immersion. On the other hand, frequency-domain parameters do not show clear differences between both stages.

5.   Discussion

The main goal of this work is to study the ANS response during a scuba diving activity while the divers were developing physical tasks inside the water. To that end, an analysis of HRV using time-domain parameters and the SPWVD time-frequency method was performed to characterize the fast response of the ANS to the immersion. A comparison between the two stages (baseline and immersion) is carried out to study how the scuba diving activity affects the ANS response.

Time-domain parameters show a significant increase in HRM and a significant decrease in $RMSSD$. This points out to an activation of the sympathetic system. These results are in contrast with previous works, where a HRM decrease has been reported in hyperbaric chamber [1–3] and in immersions [4,6]. This sympathetic activation could be explained by different factors: one could be the predominance of the physical activity and the stress of the challenging environment during the immersion [15]. Another factor is the stress related to the immersion: some studies reported that an immersion performing a stressful task could increase the HRM and the sympathetic activity [5]. The effect of cold water, that also increases the

HRM [16], could be another factor.

On the other hand, frequency-domain parameters do not show any significant differences between the two stages. There is neither a sympathetic activation registered in the $PLFn$ and $R_{LF/HF}$ as reflected in the time-domain parameters, nor a parasympathetic activation registered in the PHF as the bibliography suggests [1, 3, 4, 6]. A possible explanation of this is the low number of subjects. In fact, our database is larger (15 subjects), but only 6 have been studied because respiratory rate falls into the LF band in the excluded subjects, which could cause an overestimation of the PLF and, consequently, an underestimation of the PHF [17]. In future studies, a new algorithm to extract the frequency-domain parameters that overcome with the respiratory rate limitation and take into account non-linear relationships of the HRV should be used.

6.   Conclusion

A study of the ANS response during a scuba diving activity while the divers were developing physical tasks has been performed using time-frequency methods. Time-domain parameters suggest an activation of the sympathetic activity during the immersion. However, frequency-domain parameters do not show any change between baseline and immersion stages. In future studies, the use of alternative methods to compute the ANS frequency content taking into account the intrinsic non-linear dynamics and the influence of respiration is recommended.

Acknowledgements

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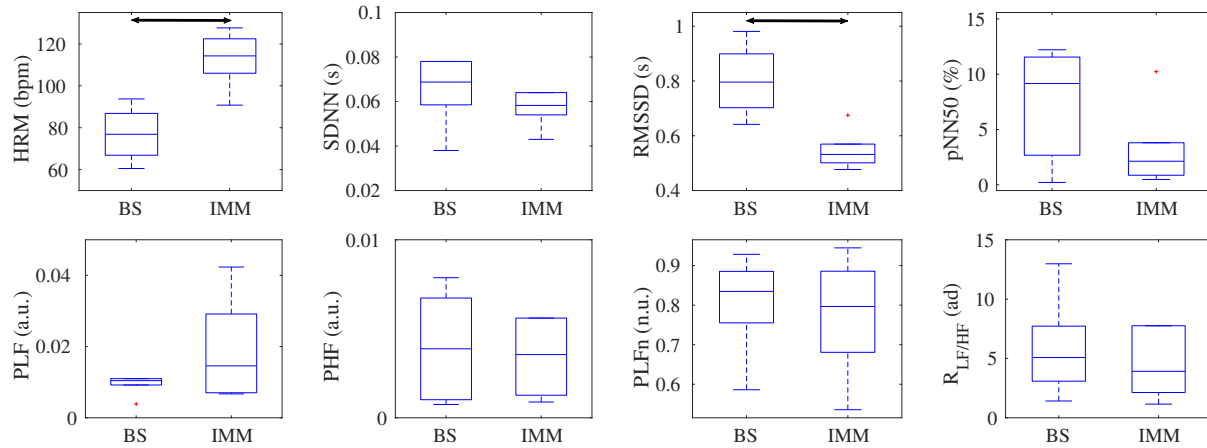
Figure 2. Boxplots of the time-domain and frequency-domain parameters from baseline and immersion stages during the reservoir immersion. Significant differences are represented by a double arrow.

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