Modeling Gender Differences in Heart Rate During the Diving Reflex: Insights into Physiological Adaptability

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Abstract

The diving reflex, a mechanism allowing mammals to sustain apnea and reduce oxygen consumption through bradycardia, is of interest due to its unclear physiological mechanisms and clinical implications. Temperature, depth, and individual physiology may influence this response. The aim is to model gender-specific differences in heart rate (HR) reduction during the diving reflex. The study enrolled 44 volunteers (17 men, age = 30 ± 13.30; 27 women, age = 24.62 ± 10.71). It comprised three phases, including baseline HR measurement (5 mins), three apnea episodes, and a recovery phase (10 mins). HR was monitored using a Firstbeat sensor, and parameters such as LF power, HF power, and LF/HF ratio were calculated. An exponential function ($rr = a + b * exp(\tau * t)$) was used to model bradycardia during the diving phase. Results revealed that women exhibited a stronger initial bradycardic response, with $\tau\_male = 0.025$ compared to $\tau\_female = 0.035$ during the first apnea. However, this difference lessened in subsequent apneas, suggesting adaptation. LF/HF is higher in women before the first apnea, but smaller after that. In conclusion, gender-specific variations in the diving reflex can be quantified using mathematical models and HRV parameters. These findings underscore the adaptability of the human body to extreme conditions, calling for further investigation into underlying physiological mechanisms.

1. Introduction

The diving reflex is a physiological response observed in air-breathing vertebrates when immersed in cold water. This adaptive mechanism primarily serves to facilitate apnea and reduce oxygen consumption by inducing a significant reduction in heart rate. The objective of this response is to conserve oxygen reserves, thus ensuring survival during periods of submersion in aquatic environments [1]. A distinguishing feature of this reflex is diving bradycardia, characterized by a substantial decrease in heart rate, which plays a central role in various adaptive responses during diving, ultimately enabling extended submersion [2].

Despite the profound relevance of the diving reflex, many underlying physiological mechanisms and clinical implications remain unclear. The response appears to be influenced by several variables, including water temperature, depth, and individual physiological factors such as gender, contributing to the complexity of this phenomenon [3].

The aim of this paper is to investigate potential gender differences in diving bradycardias. While prior research has explored various physiological aspects of diving, limited attention has been given to the specific impact of gender on bradycardic responses. We propose to use an exponential model to characterize bradycardia, by fitting the model to the RR-interval time series recorded during the apnea. The application of exponential models to the observed data enables the estimation of crucial parameters, including the time constant, amplitude, and recovery rate of bradycardia. Additionally, we propose to use Heart Rate Variability (HRV) analysis, extracted from RR-interval series before the apnea and between two more apneas, to characterize the autonomic nervous system's influence on the diving reflex. Specifically, we compute frequency domain indices, such as LF/HF ratio [4].

The structure of the paper is as follows. In Sections 2 and 3, HRV and exponential modeling of the bradycardia are detailed. In Section 4, the experimental protocol and the whole dataset are explained. In Section 5, results are reported. Finally, in Section 6, conclusions are presented.

2. Heart Rate Variability Indices

HRV refers to the natural fluctuations in the time intervals between successive heartbeats. HRV is widely employed to assess neurocardiac function, stemming from the intricate, non-linear interactions between the heart, brain, and autonomic nervous system.

In the study of HRV, it is conventionally presumed that

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short-term and long-term variations in heart rate heart rate have distinct physiological origins, and the magnitude of these variations serves as an indicator of the subject's autonomic state [5].

HRV is usually assessed by time-domain and frequency domain indices computed on NN-interval time series from 24-hour Holter recordings. Several studies have shown that both short-term (approximately 5 minutes) and long-term (over 24 hours) HRV measurements are associated with adaptability, health, mobilization of limited regulatory resources, and overall performance [5]. Recent studies showed that ultra-short-term ($\leq$ 5 min) can be used to obtain reliable HRV measurements [6].

Frequency domain HRV indices compute the power in a given frequency band from the power spectrum, in particular, $P_{LF}[ms^2]$ is the power in the *low frequency band* $[0.04, 0.15]$ Hz and $P_{HF}[ms^2]$ is the power in the *high frequency band* $[0.15, 0.4]$ Hz. In this work, we proposed to use the LF/HF ratio which represents the ratio P_{LF}/P_{HF}. The LF/HF ratio is often used as an indicator of sympathovagal balance. An increase in the LF/HF ratio suggests a relative predominance of sympathetic activity, while a decrease suggests a relative predominance of parasympathetic activity [5].

3. Bradycardia Modeling

The apnea segments are extracted from the RR-Interval time series and then normalized by the mean baseline heart rate for each subject. The reduction in the heart rate induced by the diving reflex is modeled using the following exponential function:

$$f(t) = a + c\mathrm{e}^{\tau t} \qquad (1)$$

where *t* represents the independent variable where the data is measured, namely, time; τ is the time constant that determines the rate at which the function grows, representing how strong the bradycardia response is; and *a* and *c* are intercept and amplitude parameters, respectively. Note that, since we are working with RR-interval time series, the reduction in heart rate is represented as an increase in the RR-interval, so that the exponent τ is positive and represents the increasing rate of change of the RR-interval.

The exponential curve is then estimated for each segment (apnea) and for each patient. Population estimates are obtained for each group, males and females, separately.

4. Experimental Protocol and Dataset

Our study recruited 44 volunteers, comprising 17 male subjects (age = 30.05 $\pm$ 13.30 years) and 27 female subjects (age = 24.62 $\pm$ 10.71 years). The Ethics Committee of Universidad Rey Juan Carlos approved this study under

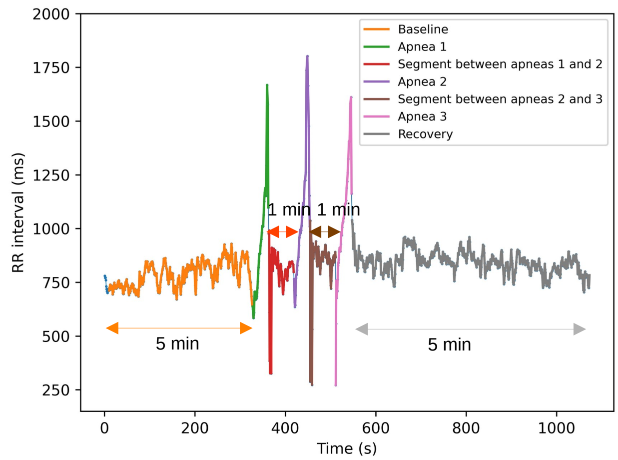


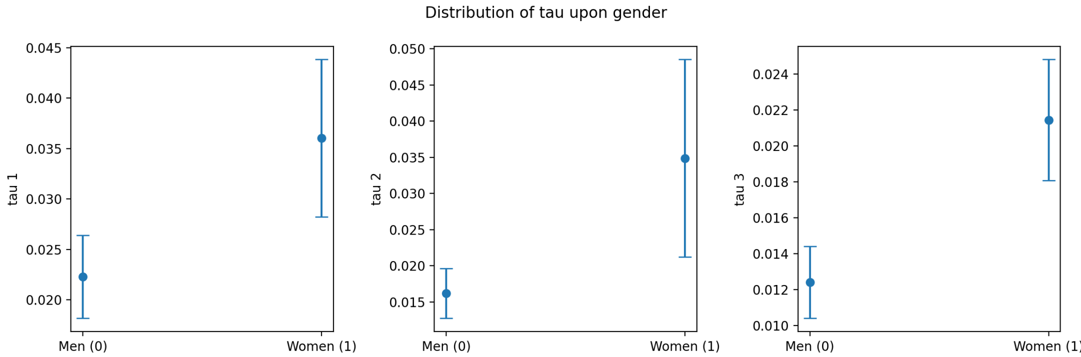
Figure 1. RR-Interval time series segmented according to the experimental protocol with the three apnea phases and the baseline, inter-apnea, and recovery segments.

the reference number ENM24/01503202209722, and all participants provided their consent. The experimental procedure comprised three consecutive phases, with continuous monitoring of heart rate utilizing the Firstbeat® sensor. To mitigate potential circadian rhythm effects on HRV, the experiment was meticulously scheduled within a consistent time frame, namely between 3 p.m. and 6 p.m. This approach allowed for a comprehensive exploration of the impact of apneas on heart rate dynamics. Before the onset of the experiment, a 5-minute baseline heart rate measurement was conducted to establish a reference point for subsequent phases. Subsequently, participants were instructed to submerge their faces in cold water, during which three apnea periods were measured, interspersed with 1-minute rest intervals. Finally, a 10-minute recovery phase was integrated into the experimental design, enabling heart rate recovery after the apnea challenges. Figure 1 shows an example of a complete RR-interval time series recorded during the whole protocol for a subject. The different phases of the protocol are indicated with different colors.

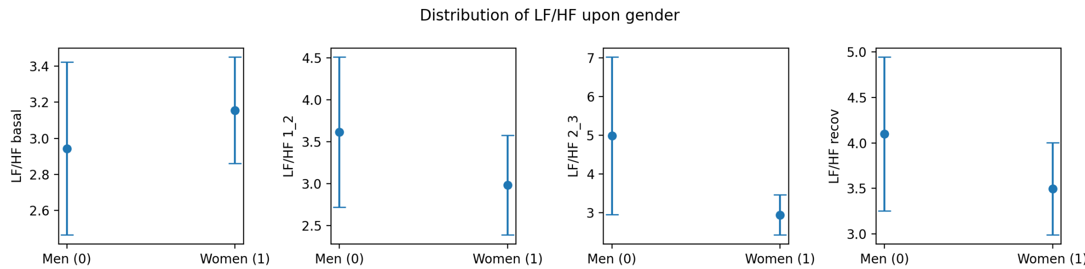
RR-Interval time series were preprocessed to detect artifacts, which are defined as intervals shorter than 300 ms. or longer than 1300 ms. Since the bradycardia induced by the diving reflex during Apnea segments could create physiological RR-intervals longer than 1300 ms, apnea segments were manually corrected.

5. Results

Figure 2(a) shows the average value and standard deviation of the τ constant of the exponential model for the bradycardias in the three apneas. In the three cases, the



(a)Average and standard deviation of τ parameter by gender during the three apneas



(b)Average and standard deviation of LF/HF ratio by gender before, between, and after apneas

Figure 2. Comparison of τ parameter and LF/HF ratio by gender in different apnea conditions.

τ constant is larger for women than men. Therefore, on average women reduce faster their heart rate during bradycardia. The standard deviation for men is smaller than the women, which showed greater variance in the τ parameter. This effect can be also shown in Figure 3 which shows the average exponential model for women (blue) and men (orange) for the three apneas. It is clear that, on average, in the three apneas the heart rate decreases (RR-interval series increases) faster for women.

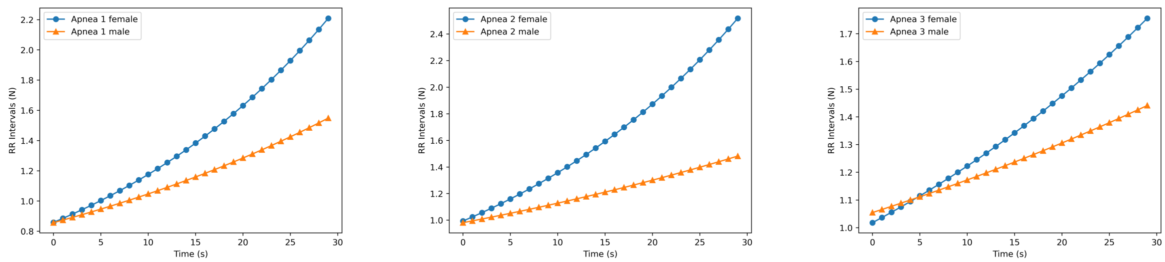
Figure 2(b) shows the average value and standard deviation of the LF/HF ratio for men and women in the following segments: (1) basal, i.e. 5 mins before apneas; (2) between apneas (LF/HF 1_2: between apnea 1 and 2; LF/HF 2_3: between apneas 2 and 3), (3) recovery, 10 mins after apneas.

The average value for men exhibits an increase between apneas when compared to the basal value. It rises from 2.9 during the basal phase to 5 between the second and third apnea. However, during the recovery phase, this value decreases to 4.1. In contrast, the average value for women experiences a slight decrease between apneas, dropping from 3.1 to 2.9. Notably, during the recovery phase, it rebounds, surpassing the basal value. It's noteworthy that, during the basal phase, women initially have a higher LF/HF ratio, but as the experiment unfolds and subjects have to perform the apnea the LF/HF ratio for men surpassed the LF/HF for women, and this gender difference becomes more pronounced. Even in the recovery phase, where the average value for men decreases to 4.1, it remains higher than the average value for women. This observation highlights the intricate interplay of gender-specific responses, where men exhibit a significant increase between apneas, while women demonstrate a more steady pattern, ultimately maintaining a lower LF/HF ratio

6. Conclusions

In this work, we performed an experimental procedure to test whether there exists any difference in the diving reflex due to gender. During the experiment, the heart rate is recorded while the subject have to perform three apnea submerging the face in cold water. We assessed the autonomic nervous system state by using frequency domain HRV indices, in particular, LF/HF ratio. The bradycardia induced by the diving reflex was modeled using an exponential model.

In conclusion, our study has provided valuable insights into the relationship between HRV and gender-specific responses to apnea. We observed that as the experiment unfolded and subjects underwent apnea challenges, the LF/HF ratio for men consistently exceeded that of women. This gender difference in LF/HF ratio became more pronounced during the experiment. Our findings support the notion that HRV indices, such as the LF/HF ratio, can serve



(a)First apnea

(b)Second apnea

(c)Third apnea

Figure 3. Average value of the exponential model for women (blue) and men (orange) for the three apneas

as indicators of sympathovagal balance. An increase in the LF/HF ratio signifies a relative predominance of sympathetic activity, while a decrease suggests a relative predominance of parasympathetic activity.

Moreover, our bradycardia modeling approach unveiled significant differences between men and women. Women exhibited a faster reduction in heart rate during bradycardia, as indicated by the τ parameter of the exponential model. This observation underscores gender-specific variations in autonomic responses.

The gender-related trends in LF/HF ratio and bradycardia response emphasize the need to consider gender-specific factors when studying autonomic responses to apnea. These findings have potential implications for medical practice and treatment strategies, as well as contributing to our understanding of gender-specific physiological differences in the context of autonomic nervous system regulation.

Further research is warranted to delve deeper into the underlying mechanisms of these gender disparities and their potential clinical significance. By expanding our knowledge in this area, we can enhance our ability to tailor medical interventions and therapies to better suit individual needs.

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