Heart Rate Variability Analysis During Exercise in Hypoxia Chamber

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***Abstract*—Heart Rate Variability (HRV) is an important measure to understand the overall physical fitness of an individual especially in cardiovascular training. Clinical applications of HRV are well established for assessing cardiovascular and metabolic illness. Recent observations have suggested its applicability in physical exercise training as well. There is still more understanding needed in the use of HRV for interpreting the internal effects of physical exercise and planning the training routines accordingly. Athletes show more interest in hypoxia training or high-altitude training to improve their exercise performance at sea level and to acclimatize to compete at high-altitude regions. It is important to understand the changes in HRV parameters of the subjects while training in a hypoxia chamber. In this study, we have analysed both the time-domain and frequency-domain HRV parameters and the Heart Rate (HR) values to understand the effects of training inside a hypoxia chamber. The changes in HRV parameters during cardio training sessions over 3 weeks for a study group of 4 subjects are reported in this study. Over the weeks, there was an increase in the total HRV and hence a decreasing LF/HF trend. pNN25 also decreased over the 3 weeks whilst rMSSD showed an increasing trend. Also, the recovery rate for the second minute of exercise cessation has been reported where a decrease of 55±6 bpm from the maximum HR was observed for the study group for week 3 when compared to 30±5 bpm for week 1, thus proving the effectiveness of hypoxia training. In addition, the changes observed in the maximum HR values during strength training sessions also decreased by 21±4 bpm over 3 weeks for the study group, which again proves the significance of hypoxia training.**

***Index Terms*—HRV, physical training, hypoxia condition, cardio training, recovery rate, strength training**

I. INTRODUCTION

Heart rate variability (HRV) is a measure that quantifies the time interval between the consecutive R peaks. It is computed from the Electrocardiogram (ECG) waveforms by measuring variations in the beat-to-beat interval and is represented in milliseconds (ms) precision. This variation is controlled by a primitive part of the nervous system called the Autonomic Nervous System (ANS). It works regardless of our desire and regulates the heart rate (HR), blood pressure (BP), breathing, digestion and also helps in maintaining the homeostasis. The ANS is subdivided into two major components, the Sympathetic Nervous System (SNS) which helps in fight-or-flight response and the Parasympathetic Nervous System (PNS) which helps in relaxation process. HRV is a non-invasive way to identify the ANS imbalance.

HRV has high clinical importance because of the fact that it acts as an early indicator of cardiovascular abnormalities and is a strong predictor of cardiovascular risk and all-cause mortality in both primary and secondary prevention settings [1]. A low HRV is associated with an increased risk of death and cardiovascular disease. People who have a high HRV may have greater cardiovascular fitness and be more resilient to stress. Exercise training may decrease cardiovascular mortality and sudden cardiac death. Regular exercise training modifies the cardiac autonomic control and individuals who exercise regularly have a 'training bradycardia' (i.e., low resting heart rate) and thereby have higher HRV than sedentary individuals [2].

The SNS and PNS influence the functions of the internal organs in a different manner, where SNS activates a physiological response and PNS inhibits it and vice versa. During exercise, 'feed-forward' inputs are sent from the brain and the SNS is activated which in turn increases the HR. This causes parasympathetic withdrawal i.e reduction of cardiac PNS activity. [3]. This withdrawal is due to the 'feed-back' from the muscle mechanoreceptors and the cardiopulmonary baroreceptors. During exercise cessation, the opposite reaction happens where the PNS takes control, resulting in decrease of HR and re-activation of the PNS. Thus both the SNS

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and the PNS are responsible for the relative balance-shift of 'sympathetic activation' during high intensity exercise and 'parasympathetic activation' during low intensity or no exercise [4].

Both time-domain and frequency domain analysis can be done for understanding the variability in the HRV parameters. Time-domain HRV parameters like Standard Deviation of RR intervals (SDRR), Percentage of successive RR intervals that differ by more than 25 ms (pNN25), Root Mean Square of Successive RR interval Differences (rMSSD), etc., are useful in quantifying the amount of variability in time period between successive heartbeats. Frequency-domain parameters estimate the distribution of absolute or relative power into multiple frequency bands namely, Ultra-Low Frequency (ULF), Very Low Frequency (VLF), Low Frequency (LF), and High Frequency (HF) bands [5] [6]. The ULF band ($<$0.003 Hz) indexes fluctuations in inter-beat intervals (IBIs) with a period from 5 min to 24 hrs and is measured using a 24 hr recordings. Oscillations with periods between 25-300 seconds (s) comprises of 0.0033–0.04 Hz and comes under the VLF band. The LF band, 0.04–0.15 Hz consists of rhythms with periods between 7-25 s and is affected by breathing rate varying from 3 to 9 breathings per minute (bpm). Within a 5 min sample, there are 12–45 complete periods of oscillation. The HF or respiratory band (0.15–0.40 Hz) is influenced by breathing from 9 to 24 bpm.

Out of these frequency bands, the LF/HF ratio is used to estimate the activities of SNS and PNS and to estimate if the person is in a relaxed or stressed state [7]. A low LF/HF ratio is a result of parasympathetic dominance and it can be concluded that the person is in resting or relaxed state, whereas a high LF/HF ratio is the result of sympathetic dominance.

II. HRV IN PHYSICAL EXERCISE TRAINING

A. *HRV during exercise*

HRV can be used as a metric for improving the physical fitness and training intensity of athletes since it reflects the major regulatory processes after physical exercise. There are many studies which have performed HRV analysis during exercise [8] [9], in which they have reported the usage of different exercise modalities like treadmill and cycling. These authors report that HRV varies with increasing intensity, prolonged duration and exercise modality, whereas a few other authors report that HRV is not dependent on the above-mentioned parameters [10] [11]. There is another study which shows increasing trend in HR and decrease in HRV during the exercise phase due to parasympathetic withdrawal, but there were no changes observed in LF/HF ratio during varying exercise intensities [11]. Owing to these contradicting results in variations of HRV during exercise, a detailed analysis is necessary in terms of finding the LF/HF ratio during baseline, exercise phase, recovery phase and post-exercise phase.

B. *Significance of hypoxia training*

It is important for athletes to train at various altitudes to improve their endurance levels. In recent times, athletes are interested in hypoxia training, to improve their sea-level athletic performance. As altitude increases, there is a decrease in atmospheric pressure and partial pressure of oxygen, thus reducing the oxygen availability for the exercising muscles. To compensate for the decrease in oxygen, erythropoietin (EPO) hormone is released by the kidney. This EPO hormone stimulates the bone marrow to produce more red blood cells which in turn increases the oxygen-carrying capacity of the blood and delivers adequate oxygen to the muscles. Increased quantities of EPO has significant effect on increasing the exercise capacity of the athletes [12]. Hypoxia training is a simple means of increasing or modifying exercise stimulus at the muscular level and to varying training stress and adaptation within the annual training plans of well-trained athletes. Oxygen-altitude classification chart has been tabulated in table I for reference.

The main strategies of hypoxia include,

- 'Live High - Train Low' (LHTL), where the athletes are living at high altitudes and training at simulated low altitude conditions
- 'Live Low - Train High' (LLTH), where the athletes are living at low altitude regions and train at simulated high altitude conditions
- Combining both LHTL and LLTH

Recently, training using LLTH method at high intensities has gained attention among the athletes. The current study reports observations made during training at LLTH condition in different exercise modalities namely, cardio training and strength training inside a hypoxia chamber.

C. *HRV under hypoxia condition*

Hypoxia training has mainly two methods namely, resting under hypoxia condition for altitude acclimatization and exercising under hypoxia condition for improving their performance. Both the methods are adapted by the athletes to enhance their endurance and training stimulus. The effects of hypoxia training are dependent on the dose, duration and intensity of the exercise performed as mentioned in [13]. Yamamoto et. al [10] have reported a decreased PNS activity as well as increased SNS indicators during sub-maximal exercise at 3500 m, in comparison with exercise done below 2500 m. Also, there were no modulations in resting HR and HRV during acute exposure to altitude. But there is a study which shows reduced cardiovascular response during hypoxia training and hence improvement in the cardiac output [14],

TABLE I: Altitude - Oxygen chart

Altitude (feet)	Altitude (meters)	Effective Oxygen(%)	Altitude category
500	152	20.9	Sea-level
2000	610	19	Low
4000	1219	17.9	Medium
6000	1829	16.6	Medium
8000	2438	15.4	High
10000	3048	14.3	High
15000	4572	11.8	Very high

using rMSSD parameter to understand hypoxia-related stress on cardiac autonomic functioning.

D. Heart Rate Recovery

Heart Rate Recovery (HRR) is a very good indicator of cardiac efficiency and cardiac responsiveness during physical training. The shorter it takes for the heart rate to get back from maximum to normal levels soon after exercise cessation, the healthier the person is and vice-versa. Parasympathetic activation which occurs immediately after the termination of physical exercise is strongest during the first 30 seconds [15]. Upon exercise cessation, HRV measures show a slower recovery with greater intensity of preceding exercise. Variations in HRR dependency during various exercise durations, intensities and doses has not been clearly elucidated [3]. Alvarez et al., have reported that the decrease in post-exercise HR is exponential because of the mediated sympathetic activity and steady plasma clearance of metabolites caused by high-intensity exercise [16]. Also, they have claimed that high intensity physical training programme performed under hypoxia conditions improve the HRR during the first 3 minutes after exercise cessation, when compared with the same training carried out under normal conditions.

Studies which discuss resting autonomic responses to acute exposure at high altitude are not well established and hence it is necessary to focus on the immediate recovery period i.e 2-5 min immediately after the cardio session. This study is designed to understand the changes occurring in HRV parameters while performing cardio and strength training under hypoxia conditions, followed by the recovery period after exercise cessation.

III. METHODOLOGY

A. Study design

To analyze the HRV changes under hypoxia conditions, a data collection exercise was performed at Centre for Sports Science (CSS), Sri Ramachandra Institute of Higher Education and Research, Chennai, India. The study was approved by the ethical committee of Sri Ramachandra University. Data collection was planned for a duration of 3 weeks, 1 day/week (every Friday) inside a hypoxia chamber, where the oxygen concentration was maintained at 13% i.e oxygen equivalent at an altitude of 3658 m above the sea level. Fig.1 shows the subjects working out inside a hypoxia chamber under trainers' supervision.

TABLE II: Subject meta data

Subject ID	Age	Gender	Height (in cm)	Weight (in kg)
Sub - 01	35	M	168	68
Sub - 02	27	M	172	60
Sub - 03	33	F	162	71
Sub - 04	27	M	168	61

Fig. 1: Cardio and strength training inside hypoxia chamber

B. Subject selection

4 suitable subjects (3 male & 1 female) satisfying the following inclusion and exclusion criteria were selected for the study. Subject meta data is tabulated in table II.

1) Inclusion criteria:

- Age: 20 - 45 years
- BP: <140/90 mmHg
- Active life style (at least 30-40 minutes of daily physical activity)

2) Exclusion criteria: Volunteers with any of the below conditions were excluded from the study

- Cardiovascular, pulmonary, metabolic or musculoskeletal disorder
- Inability to refrain from smoking, caffeine or alcohol ingestion the day before or on the day of the test
- Respiratory illness in the preceding two weeks

The purpose and procedure of the study were clearly explained to the subjects. All the participants were neither professional athletes nor followed a sedentary lifestyle and were short-distance marathon runners. The subjects were instructed not to consume caffeine or food two hours prior to the exercise session. A sample data collection was performed on day 1 to see if the subjects were able to adapt to hypoxia conditions and perform physical exercise without any fatigue.

C. Exercise protocol

R-R interval data was collected using the Suunto Movesense HR sensor which has a sampling rate of 125 Hz for raw ECG signal along with a 8 ms resolution for R-R data. The sensor can be worn using a chest belt. The belt is worn around the chest such that the sensor is placed exactly at the lower tip of the sternum and the electrodes are firmly in contact with the body. After wearing the chest belt, the subjects were asked to do basic warm-up exercises for about 4-5 minutes which included static stretching and joint mobility exercises outside the hypoxia chamber.

The main training session was done inside the hypoxia chamber as per the following protocol:

- Cardio session which includes 30 minutes of cycling/treadmill where the execution speed was controlled by the subjects as per their comfort.

- This session was followed by an immediate recovery period of 5 minutes.
- Exercise cessation recovery was followed by strength training for a duration of 45 minutes which consists of the following exercises: Squats, deadlift, bench press, bentover row, shoulder press, pull-up, plank and wood chops. Each exercise is repeated 12 times per set for 3 sets, followed by a resting period of 60-90 seconds after each set.

During the training session, optical-based HR and SpO_2 readings were taken once in every 15 minutes right from the warm-up session, in order to ensure that the subject does not experience any fatigue due to working out in hypoxia condition. The subjects were asked to lie down in supine position outside the hypoxia chamber for 15 minutes for physical and mental relaxation.

IV. DATA ANALYSIS

A. HRV analysis

For HRV analysis of the cardio session, the whole 30 minutes data was used. The data was divided into 5-minute windows and the noisier sections were removed manually. Time-domain features like pNN25 and rMSSD and frequency-domain features like LF power, HF power, LF/HF ratio and Total Power (TP) were used for analysis. The spectral analysis was done using Welch's periodogram estimation method and the sampling rate used for data interpolation was 4 Hz. The changes observed in these parameters over the course of training session i.e the change in values of week 3, when compared to week 1 is reported in this study. For reporting, the values obtained during the last 5 minutes of the cardio session were taken, since the influence and fatigue due to training for the first 25 minutes would be reflected during this period.

B. HR analysis

To understand the influence of hypoxia training during the strengthening session, the changes in HR values over the weeks were considered. The maximum HR values for each week was calculated and the change in these values for each week were used to understand the effects of hypoxia training during strengthening sessions. HR was computed using the raw R-R interval data and was averaged for the whole duration of the strengthening session. HRV analysis was not considered for strength training since, the duration of each repetition is $<$30 s and hence is too short to perform spectral analysis.

To understand the influence of hypoxia training during recovery period, the changes in the HR values over the weeks has been computed. The maximum HR value during the end of cardio session is taken and the drop in HR values after 1 minute and 2 minutes is used to understand the influence of hypoxia training during recovery period.

V. RESULTS AND DISCUSSION

A. Cardio session

There was no particular speed maintained during the cardio session and was varied by the subjects according to their convenience. Nevertheless, this was done to understand the acute physiological response to training sessions in hypoxia condition as typically performed by runners in real world situations, which increases the practicality of the current study. Since this was the first time for the subjects to train inside a hypoxia chamber, the speed control was not considered during cardio session as reduced speed could compensate for the reduced O_2 levels [14].

Short-term HRV analysis i.e a window duration of 5 minutes is used for computing the time-domain and frequency-domain parameters during cardio session. The rMSSD parameter is calculated as the time difference between the successive R-R intervals and these values are averaged before taking their square roots. rMSSD is a primary time-domain parameter since the influence of the PNS can be understood from it [6]. Higher the rMSSD values, more the influence of the PNS. Lower HR values are inversely proportional to the rMSSD value, since the SNS dominance is comparatively lower and the person is able to do physical exercise with minimal efforts. rMSSD is an important parameter to understand the HF changes in HR and helps to identify the parasympathetic modulation [17]. The rMSSD values for subject 4 is plotted in fig.2. R-R data during cardio session after noise removal was used for plotting. The x-axis represents the duration of the cardio session in minutes and the y-axis represents the changes in rMSSD values in s^2. During the last 5 minutes of week 1, the rMSSD value is $0.0081s^2$, during week 2 it is $0.0094s^2$ and during the last week, the value is $0.016s^2$. Hence, an increasing trend in the rMSSD values is observed, which shows that the higher influence of the PNS. This shows that the subject was able to perform cardio training with minimal efforts during the last week when compared to first week and hence hypoxia training has helped in improving the cardio performance of the subject.

The percentage of adjacent R-R intervals that differ from each other by more than 25 ms is represented as pNN25. It is also one of the most important time-domain parameters which has direct correlation with PNS activity. Reduced pNN25 value corresponds to a reduced cardiac activity and hence the person is able to perform cardio training with minimal effort [17]. Fig.3 shows the pNN25 values over the 3 weeks for subject 4 and the last 5 minutes are considered for reporting. pNN25 during week 1 is nearly 100% showing that the person has used maximum cardiac effort and the influence of SNS is higher. During week 2, it has reduced to 98.4 % and during week 3 it has reduced to 92.5%. This decreasing trend in pNN25 values over the weeks shows the reduced influence of SNS. This once again proves that hypoxia training improves the cardiac efficiency.

Frequency-domain analysis was also done for the cardio session data and the trends in these values were tabulated. LF/HF ratio is an important parameter to understand the influence of both SNS and PNS simultaneously, where SNS contributes to LF power and HF contributes to HF power. Lower HF ratio indicates a higher HF power value due to higher influence of SNS. A decreasing trend in LF/HF ratio over the weeks was observed showing the changes in SNS activity due to the influence of hypoxia training. The overall comparative table of time-domain and frequency-domain HRV parameters for all the 4 subjects during the cardiac training course during week 1 and week3 has been tabulated in table III.

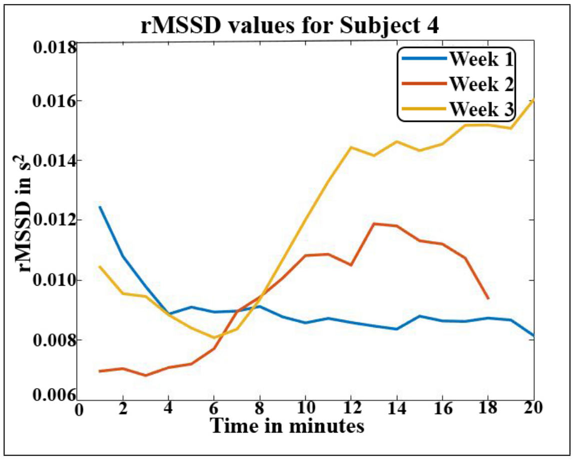

Fig. 2: rMSSD values for Subject 4 during cardio training session

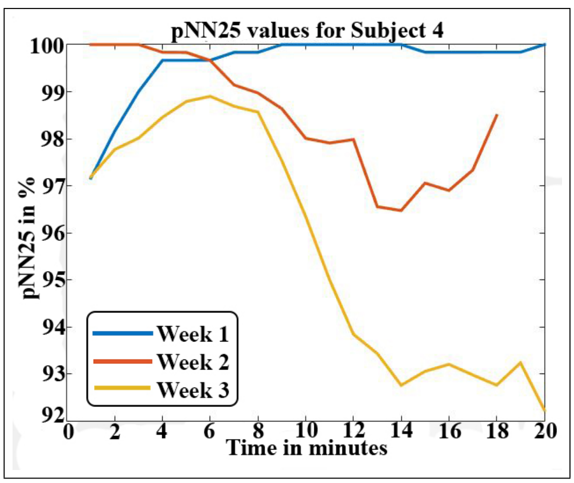

Fig. 3: pNN25 values for Subject 4 during cardio training session

TABLE III: Comparison table for changes in HRV parameters for week 1 and week 3 of hypoxia training

HRV parameters	Week 1	Week 3
pNN25	99.38 (0.84)	96.84(0.34)
rMSSD	67.08 (5.46)	61.62 (3.666)
LF/HF ratio	2.45 (0.67)	1.76 (0.21)
LF	67.08 (3.12)	31.2 (5.772)
HF	31.2 (5.772)	19.5 (2.028)
TP	244.92 (63.102)	165.75 (33.696)

*The values represented are mean (±% SD). pNN25 values are expressed in terms of %, rMSSD values are expressed in ms, Low Frequency (LF), High Frequency (HF) and Total Power (TP) values are expressed in ms^2

B. Recovery period

The decrease in HR during the first minute immediately after exercise cessation is commonly considered as HRR and is important to understand the cardiovascular functioning of the athlete. A recovery HR of 25-30 bpm during the first minute is considered as a good recovery score and this rate should increase over the period of time. This increase in HRR rate over the weeks is an indicator that the fitness levels of the athlete is improving. The recovery HR values for first minute after exercise cessation (HRR1) and second minute after exercise cessation (HRR2) for all the subjects over the 3 weeks has been shown in fig.4. In case of subject 4, the maximum HR during week 1 is 153 and a recovery of 33 bpm has occurred during the first minute and a recovery of 50 bpm has occurred during the second minute. During the last week, i.e week 3, the subject's maximum HR is 176 and recovery rate during the first minute is 40 bpm and during the second minute is 64 bpm. When compared to week 1 and week 3, the recovery rate has increased over time, thus indicating that the fitness level of the athlete has increased while training inside a hypoxia chamber.

C. Strength training

For analysing the subject's performance during the strength training inside a hypoxia chamber, the changes in maximum HR value over the weeks has been considered. This is again done to understand the changes in cardiac efficiency over the course of training. During the strength training, the subjects performed various muscle strengthening exercises like, squats, deadlift, pull-up, etc., each 3 sets and 12 reps. The maximum HR value during week 3 should be comparatively lower than the week 1, since the hypoxia training should have increased the cardiac efficiency of the subject and should be able to do exercise with minimum effort. The maximum HR values for

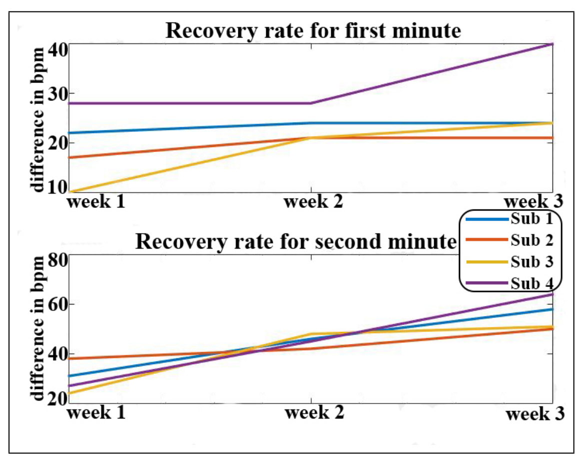

Fig. 4: HRR rate for first minute and second minute after exercise cessation. Plot a shows the recovery rate for first minute for all the subjects over the 3 weeks. Plot b shows recovery rate for second minute for all the subjects over 3 weeks

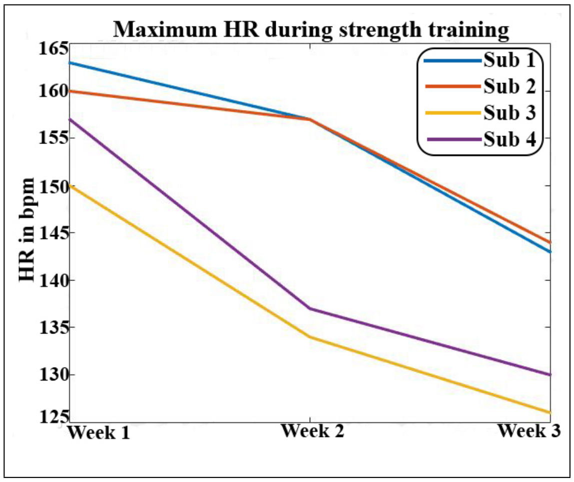

Fig. 5: Maximum HR values during strength training for all the 4 subjects

all the subjects over the weeks has been plotted in fig.5. For subject 1, the maximum HR during week 1 was 163, during week 2 it was 155 and during week 3, it was 145. A decrease of 8 bpm after the first week and a decrease of 18 bpm after the second week was observed. Hence it can be inferred that the hypoxia training has helped in increasing the cardiac efficiency where the subject is able to perform the strengthening session with minimal cardiac effort over the weeks of hypoxia training.

VI. CONCLUSION

The current study presents the changes observed in both the HRV parameters and HR values during different exercise modalities like cardio and strength training and most importantly recovery rate after exercise cessation. The study helped in understanding the influence of SNS and PNS during cardio session through various time-domain and frequency-domain parameters. This study has made important findings in terms of calculating the recovery rate post-exercise cessation where the HR values have significantly decreased during the first and second minute. The recovery rate has comparatively increased from week 1 to week 3, thus proving that hypoxia training has improved the physical fitness levels of the current study group. Also, while analysing the maximum HR values during strength training over the 3 weeks, the values have significantly decreased, thus proving that the subjects are able to perform the training with minimal cardiac efforts during the week 3 when compared to week 1. The results suggest that hypoxia training is effective and has helped in improving the fitness levels of the current study group. Our future work will include extending the study to a control group with exercise under normal conditions to validate the claim that the above mentioned improvements were indeed an outcome of hypoxia training.

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