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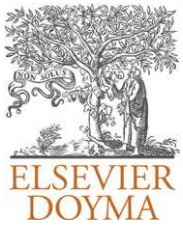

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ORIGINAL

Cardiorespiratory parameters during submaximal exercise under acute exposure to normobaric and hypobaric hypoxia

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KEYWORDS
Heart rate variability;
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Abstract Seven healthy young men were submitted twice to a hypoxia tolerance test at a simulated altitude (3000 m). Their first acute exposure was in a hypobaric chamber; and the second, in a hypoxic tent. Cardiorespiratory parameters and heart rate variability measurements were obtained under each hypoxic condition. A significant decrease of 6% to 8% compared to normal oxygen conditions was observed in arterial oxygen saturation (SpO_2) in both hypoxic conditions at rest; whereas exercise led to decreases of 10% in SpO_2 despite an increase of 27% in respiratory minute volume. The low frequency (LF) and high frequency (HF) components of heart rate variability significantly changed from normoxia (LF: 37.1, HF: 62.9, LF/HF: 1.27) to hypobaric hypoxia (HH) (LF: 49.1, HF: 50.6, LF/HF: 1.96). However, these changes were not observed under normobaric hypoxia. Thus, heart rate variability behaved differently in the two hypoxic conditions, supporting the hypothesis that normobaric hypoxia and hypobaric hypoxia are not equal stimuli to the cardiovascular and respiratory systems. A correlation was found between sympathetic and vagal modulations in normoxia and SpO_2 at exercise under hypobaric hypoxia (HH). Individuals with higher sympathetic modulation (LF%) in normoxia had higher SpO_2 at exercise under HH ($r = 0.808$, $P < 0.05$) and individuals with higher vagal modulation (HF%) in normoxia showed a trend to lower SpO_2 in exercise under HH ($r = -0.636$, $P = 0.125$). This opens up the possibility of using this correlation as a tool for predicting the individual capacity to altitude acclimatization.

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PALABRAS CLAVE
Variabilidad de la frecuencia cardiaca;
Prueba de tolerancia a hipoxia;
Tienda hipóxica;
Cámara hipobárica;
Saturación arterial de oxígeno

Parámetros cardiorrespiratorios durante ejercicio submáximo en hipoxia aguda hipobárica y normobárica

Resumen Siete jóvenes sanos y en buena condición física realizaron dos pruebas de tolerancia a hipoxia a una altitud simulada de 3.000 m. La primera fue en cámara hipobárica, mientras que la segunda se efectuó en una tienda hipóxica. Se registraron varios parámetros cardiorrespiratorios y la variabilidad de la frecuencia cardiaca. En comparación con las condiciones de normoxia, se observó un decremento significativo del 6% al 8% en la saturación de oxígeno arterial (SpO_2) en reposo en ambas condiciones de hipoxia. El ejercicio desencadenó descensos de un 10% en SpO_2 pese a un incremento del 27% del volumen minuto ventilatorio. Tanto los componentes de baja (LF) como alta frecuencia (HF) de la variabilidad del ritmo cardiaco cambiaron significativamente en hipoxia hipobárica (LF: 49,1, HF: 50,6, LF/HF: 1,96) respecto a normoxia (LF: 37,1, HF: 62,9, LF/HF: 1,27). Estos cambios no se apreciaron en condiciones de hipoxia normobárica, lo cual apoya la hipótesis de que la hipoxia hipobárica y normobárica no suponen igual estímulo para los sistemas respiratorio y cardiovascular. Se ha observado una correlación entre la modulación vagal y simpática en normoxia y la SpO_2 durante ejercicio en cámara hipobárica. Los sujetos con mayor modulación simpática (LF%) en normoxia presentan mayor SpO_2 en ejercicio en la cámara ($r = 0{,}808$, $p < 0{,}05$) y los individuos con mayor modulación vagal (HF%) en normoxia tienden a SpO_2 más bajas en ejercicio en hipobaria ($r = -0{,}636$, $p = 0{,}125$). Surge la posibilidad de utilizar esta asociación como herramienta predictiva de la capacidad individual de aclimatación a la altura.

Introduction

In newcomers to high altitude, aerobic work capacity appears to be diminished.[1–4] Individual aerobic work capacity is usually calculated by determining the maximal oxygen consumption rate (VO_2max). This parameter assesses general oxygen availability at the cell level, including oxygen diffusion and transport, and the mitochondrial processes that take place in the organism. During hypobaric hypoxia, VO_2max falls and this reduction is not wholly reversed even after restoration of oxygen uptake.[5] As a response to the partial pressure reduction of oxygen at alveolar level, there are certain changes in other physiological parameters in order to maintain oxygen uptake to the tissues. Characteristic changes elicited by altitude, as a consequence of the lower arterial pO_2, are hyperventilation, resulting in respiratory alkalosis,[6] and increases in heart rate and arterial blood pressure.[7] One of the changes observed in relation to hypoxia is an increase in oxidative stress damage.[8] It has been suggested that this phenomenon is due, at least in part, to recurrent conditions of ischemia-reperfusion, which could cause cell damage and induce signaling for apoptotic pathways.[9]

In addition, changes in autonomous nervous system (ANS) activity at moderate and high altitude have been evaluated by recording heart rate variability (HRV). This noninvasive electrocardiographic marker reflects the activity of the sympathetic and vagal components of the ANS. It expresses the total amount of variations of RR intervals (intervals between QRS complexes of normal sinus depolarization).[10] HRV analysis is widely used in exercise medicine, with a significant correlation between HRV and VO_2max reported in athletes,[11] and increased HRV indices have also been found in highly trained cyclists.[12] Preliminary studies measuring HRV during acute hypobaric hypoxia exposure reported a reduction in HRV by means of a decrease in total spectral power.[13,14] These studies demonstrated a change in the sympathetic–parasympathetic balance, in that the relative sympathetic tone increases along with a decrease in parasympathetic tone. A relationship between changes in VO_2max and HRV alterations during acute hypobaric hypoxia has also been observed, with a decrease in the power of the high (HF) and low frequency (LF) bands and an increase in the LF/HF ratio.[15,16] Moreover, recent studies on acute mountain sickness (AMS) showed that the predomination of sympathetic activity during high altitude exposure may reflect varying capacity of acute hypobaric hypoxia adaptation[17,18] and that parameters like HRV could enhance the predictability of AMS susceptibility.[18] A similar behaviour for cardiorespiratory parameters has also been described for acute simulated altitude exposure.[19,20] Simulated altitude systems are now more frequently used than ''real'' high altitude exposure. In this sense there are two types of simulated altitude exposure: hypobaric hypoxia (low pressure chambers) and normobaric hypoxia (hypoxic gas mixtures). Commercially available hypoxic tents (normobaric hypoxia) are now widely used as a complementary tool to conventional training methods, due their low cost and easy use, instead of the hypobaric chambers originally developed to simulate high altitude exposure.

In order to gain a better understanding of the changes and relationships between HRV and cardiorespiratory parameters on simulated high altitude exposure, we conducted a study in two distinct simulated altitude systems: a hypobaric chamber and a hypoxic tent. The main objective was to compare the possible different behaviour of HRV in normoxic and such hypoxic conditions and to determine if HRV could

be a complementary tool in predicting individual hypoxia tolerance in addition to the results observed by the traditional approach of monitoring arterial oxygen saturation and cardiorespiratory parameters.

Methods

Subjects

Seven healthy young men aged 22.7 ± 5.8 years (mean ± SD), weighing 71.7 ± 5.0 kg and 179 ± 7.0 cm tall, voluntarily participated in this study. Five of them were well-trained subjects, whereas the other two were recreational athletes. None of them were previously acclimatized to altitude. They were submitted twice to a hypoxia tolerance test. The first acute exposure to simulated altitude was performed in a hypobaric chamber; and the second exposure, in a hypoxic tent (see the *Hypoxia exposure procedure* section for details). In both cases they were exposed to a simulated altitude of approximately 3000 m above sea level under strict medical control and after a medical examination and electrocardiographic recording. The research was conducted with their written consent, and according to the recommendations of the Declaration of Helsinki.

Hypoxia tolerance test

The tests were done as previously described.[21] In brief breathing frequency (BF), tidal volume (V_T), respiratory minute volume (V_E), heart rate (HR), arterial oxygen saturation (SpO_2) were measured in normoxia and at simulated altitude (3000 m above sea level) at rest and during the fifth minute of exercise on a cycloergometer (Monark 825E, Varberg, Sweden) at sub-maximal workload. This sub-maximal workload was individually established as 50% of predicted maximal oxygen consumption, according to Åstrand tables and taking into account weight, age and sex. According to this, four recordings were necessary to complete the whole hypoxia tolerance test: first, at rest in normoxic conditions; second, at rest in hypoxic conditions; third, exercising at hypoxic conditions; and fourth, exercising at normoxic conditions. At each step the above mentioned ventilatory and cardiovascular parameters were measured and the cardiac and ventilatory responses to hypoxia were calculated and evaluated as described by Richalet and Herry.[22] Ventilatory exchange was recorded with a respirometer (Ohmeda 5420, Datex-Ohmeda, Louisville, KY, USA); cardiac frequency was recorded with a Polar S810i, the same cardiotachometer was used to record HRV (Polar Electro Oy, Kempele, Finland); and SpO_2 was measured in each subject with a pulse oximeter (PULSOX-7, Minolta, Osaka, Japan).

Hypoxia exposure procedure

All the subjects were submitted to the same procedure in order to record HRV measurements and the cardiorespiratory parameters under the two hypoxic conditions. All measurements were always first recorded in normoxic conditions at rest. The subjects were then exposed to simulated altitude conditions until reaching 3000 m above sea level in a hypobaric chamber (HH condition), which was gradually accomplished in 15 min. HRV and cardiorespiratory parameters obtained in resting conditions were recorded after at least 5 min of stabilization at altitude and the exercise recordings were obtained subsequently after resting registers were completed. The same protocol was repeated one week later, in a normobaric hypoxic tent (NH condition). HH exposure was performed in a hypobaric chamber (CHEx-1 Moelco, Terrassa, Spain) at the premises of *Futbol Club Barcelona*. NH exposure was attained in a hypoxic tent (Hyp 100 Hypoxic generator, Hypoxico Inc., New York, USA) located in the facilities of the *Centre d'Alt Rendiment de Sant Cugat del Vallès* (Barcelona), where hypoxia is achieved with a oxygen depletion method that equilibrates gas mixture, until the desired altitude is reached.

Heart rate variability

All HRV recordings were recorded for at least 6 min, in the same place, at the same time of day and in supine position by two different instruments: a specific ECG recorder (Omegawave Sport Technology System, Portland, OR, USA) and a model of cardiotachometer able to record R-R signals (S810i, Polar Electro Oy, Kempele, Finland). This allowed us to check linearity between these two systems.[23] Recordings were transferred via infrared port to a specific data processing program[24] (Polar Precision[24] Performance Software v.4.03.050, Polar Electro Oy, Kempele, Finland). Once viewed on the notebook screen, the data were filtered to remove any interference. Filtering was achieved with the above software tools on the base of ''moderate'' filter power with a minimum protection area of 6 beats per min. Data referring to RR interval time (ms) were then exported to an Excel (Microsoft®) file. Beginning from the first minute of recording, 300 beat-to-beat intervals were selected and stored as text format files to be processed later by means of *HRV Analysis Software 1.1*,[25] in order to analyze HRV. We evaluated the variations of HRV by time and frequency domain methods.[26] In the time domain methods, we analyzed the following statistical measurements: RMSSD, expressed in ms, which is the square root of the mean squared differences of successive R-R intervals; and pNN50, expressed in percentage, which is the proportion of the number of interval differences of successive intervals greater than 50 ms. Also in the time domain methods, we used the geometrical nonlinear Poincaré plot analysis with the ellipse fitting procedure. This plot consists of a diagram of the correlation between successive RR intervals, i.e. the plot of RR_{j+1} as a function of RR_j. The ellipse is oriented according to the line-of-identity ($RR_j = RR_{j+1}$). The transversal diameter of the ellipse characterizes the standard deviation from the points perpendicular to the line-of-identity (SD1) and describes the short-term variability of heart frequency, whilst the standard deviation along the line-of-identity (SD2) describes the long-term variability. In the frequency domain methods, we analyzed the areas of the spectral peaks of very low frequency (VLF), low frequency (LF) and high frequency (HF) components in percentage (VLF%, LF% and HF%) and normalized units (nu), LFnorm and HFnorm. The LF/HF ratio for analysis of the sympathetic–parasympathetic balance was also calculated.

Statistics

Descriptive statistics, the non-parametric comparison test and the correlation (Spearman) analysis test were carried out with GraphPad Prism 4 (GraphPad Software, La Jolla, CA, USA), and SigmaPlot 11 (Systat Software, San Jose, CA, USA) software packages. Unless otherwise indicated, data are expressed as mean values ± 95% confidence interval. Statistical significance was assumed for $P < 0.05$.

Results

Table 1 shows the values obtained in the hypoxia tolerance test performed with both artificial hypoxia systems. Under resting conditions, the only parameter that significantly changed was SpO_2, which diminished in both HH (6.2% decrease) and NH (7.9% decrease) from normoxic values. Exercise in HH elicited a significant 10% decrease in SpO_2 and a 27% increase in V_E when compared to normoxic exercise. Similar changes were observed in the same parameters for exercising individuals at NH conditions, which were accompanied by a significant increase in HR. The other respiratory parameters (V_T and BF) also showed higher values in both hypoxic conditions during exercise, although the differences were not statistically significant ($P > 0.05$). All subjects studied showed adequate tolerance to hypoxia both in the hypobaric chamber (HH) and inside the hypoxic tent (NH), as indicated by their hypoxic cardiac and ventilatory responses during exercise, which matched the normal threshold values according to Richalet and Herry.[22]

Table 2 shows the time and frequency domain measurements of HRV in normoxic and the two hypoxic conditions. Significant changes from normoxia were found only under HH conditions and in the indices HF%, LF%, LFnorm and LF/HF ratio. No statistically significant changes between normoxia and NH conditions were seen. To check the usefulness of HRV as a tool for predicting hypoxia tolerance, we analyzed the relationship between HRV indices under normoxic conditions and the response of cardiovascular parameters under acute hypoxia exposure. A statistically significant correlation ($r = 0.808$, $P < 0.05$) between LF% in normoxia and SpO_2 in exercise at HH (Fig. 1A) and an inverse correlation ($r = -0.636$, $P = 0.125$) between HF% and SpO_2 under the same conditions (Fig. 1B) were found. The variation of SpO_2 between hypoxic and normoxic conditions, as measured at rest and exercise (a parameter generally accepted as a good indicator for hypoxia tolerance), did not correlate with any HRV index. V_E during exercise in HH was not related to HRV markers under normoxia. Similarly, no correlations were found between HRV indices and the hypoxia tolerance test variables measured in NH conditions. To validate the consistency of the correlated parameters of HRV in the different situations, we studied the relationship of LF%, HF% and LF/HF ratio under normoxic and hypoxic conditions. Fig. 2 shows the correlations found under HH conditions. Significant correlation was evident in HF% ($r = 0.809$, $P < 0.05$) and LF/HF ratio ($r = 0.994$, $P < 0.001$) and a lower correlation was found for LF% ($r = 0.741$, $P < 0.057$).

Table 1 Cardiorespiratory parameters obtained by the hypoxia tolerance test in resting and exercising conditions and performed at two artificial hypoxia systems: hypobaric chamber (HH) and hypoxic tent (NH).

	REST				EXERCISE			
	HH		NH		HH		NH	
	Normoxia	Hypoxia	Normoxia	Hypoxia	Normoxia	Hypoxia	Normoxia	Hypoxia
HR (beats min^{-1})	58 ± 8	61 ± 9	60 ± 6	62 ± 6	121 ± 16	129 ± 23	126 ± 13	134 ± 16*
SpO_2 (%)	97.7 ± 2.5	91.6 ± 4.2*	96.7 ± 2.1	89.1 ± 3.8*	94.3 ± 3.9	85.3 ± 3.8*	95.3 ± 1.4	86.0 ± 1.7*
V_E (L min^{-1})	10.2 ± 5.3	10.5 ± 4.9	12.0 ± 4.2	10.3 ± 1.8	28.1 ± 5.3	35.7 ± 5.9*	31.5 ± 4.5	39.7 ± 6.7*
V_T (L)	0.77 ± 0.30	0.81 ± 0.36	0.80 ± 0.30	0.82 ± 0.21	1.65 ± 0.52	1.85 ± 0.56	1.80 ± 0.60	1.91 ± 0.53
BF (cycles min^{-1})	12.9 ± 2.7	13.3 ± 4.0	15.3 ± 2.6	13.4 ± 4.7	18.1 ± 4.5	20.4 ± 5.4	19.3 ± 6.0	22.3 ± 7.4

Significant differences ($P < 0.05$) between hypoxic and normoxic conditions for each artificial hypoxia system are indicated by an asterisk (*). HR, heart rate; BF, breathing frequency; SpO_2, arterial oxygen saturation; V_E, respiratory minute volume; and V_T, tidal volume.

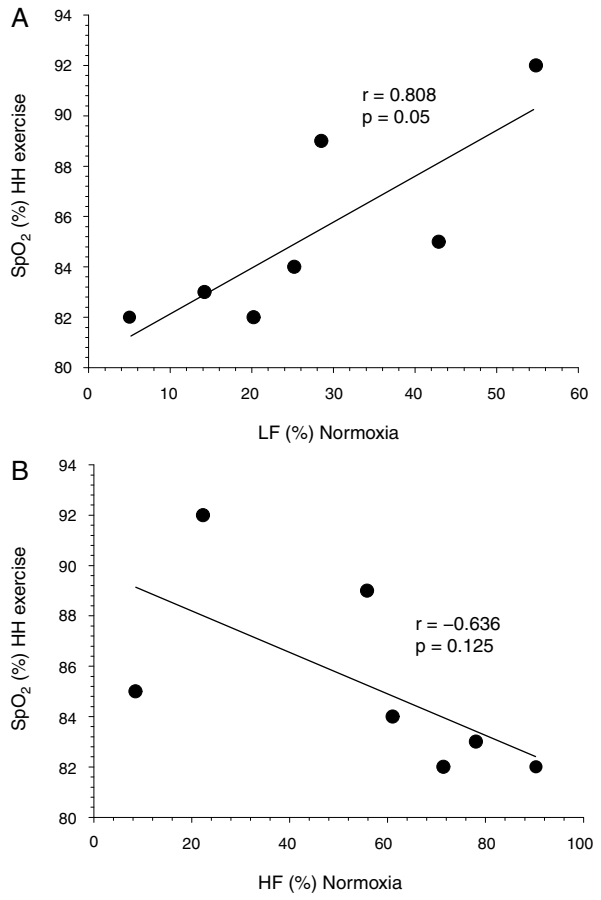

Figure 1 Correlation plots between LF% and HF% and SpO_2 in exercise under HH conditions.

Discussion

Two major findings are reported in this study: the unexpected differences in the behaviour of some cardiorespiratory and HRV parameters between the two artificial hypoxia systems used; and the correlation between some HRV measurements in normoxia to SpO_2 in exercise at HH. This study has two constraints: first a relatively low number of subjects studied ($n = 7$), although individual characteristics were quite homogeneous, and second the analysis of HRV is not only influenced by physiological components but also, and at a variable extent, by some psycho-emotional factors.[27–29]

Differences in cardiorespiratory and HRV parameters after hypobaric and normobaric hypoxia exposure

SpO_2 at rest diminished more strongly with exposure to NH than to HH, and V_E was higher in NH at exercise than under HH conditions (Table 1). These differences are due to two main factors. First, there is a slight reduction in air density under hypobaric conditions that justifies a higher ventilation rate for the same work load of the respiratory muscles. Second, as a consequence of the different gas inflow rates into each hypoxic system, a different gas composition (mainly concerning relative humidity and carbon dioxide accumulation) in the two hypoxic conditions can be assumed, leading to a relatively more hypercapnic situation in the hypoxic tent than the hypobaric chamber, as discussed below. Unfortunately, an accurate measurement of gas composition in the hypoxic tent, in order to corroborate this hypothesis, was not made during the experimental performance. Afterwards, before all data were processed, the physical arrangement of normobaric hypoxia system was changed, making impossible to check it in the original conditions.

Table 2 Time and frequency domain measures of HRV in normoxic and the two hypoxic conditions: hypobaric hypoxia in the hypoxic chamber (HH) and normobaric hypoxia in the hypoxic tent (NH).

	HH		NH	
	Normoxia	Hypoxia	Normoxia	Hypoxia
VLF (%)	17.4 ± 15.0	26.2 ± 15.9	21.4 ± 11.2	23.7 ± 9.7
LF (%)	27.3 ± 17.0	34.4 ± 14.6	36.9 ± 15.2	37.8 ± 12.2
HF (%)	55.3 ± 29.8	39.4 ± 22.3*	41.7 ± 20.7	38.6 ± 18.0
LF (nu)	37.1 ± 29.1	49.1 ± 26.0*	48.5 ± 22.1	50.5 ± 17.6
HF (nu)	62.9 ± 29.1	50.6 ± 25.5*	51.5 ± 22.1	49.5 ± 17.6
LF/HF	1.27 ± 1.84	1.96 ± 2.6*	1.34 ± 1.12	1.28 ± 0.92
RMSSD (ms)	55.4 ± 29.3	54.9 ± 26.6	56.2 ± 25.6	47.9 ± 23.7
pNN50 (%)	35.8 ± 26.1	32.5 ± 22.1	31.7 ± 21.6	27.2 ± 20.0
SD1 (ms)	39.5 ± 20.8	39.2 ± 18.8	40.1 ± 18.2	34.2 ± 16.9
SD2 (ms)	70.4 ± 28.5	90.4 ± 34.8	89.9 ± 34.2	66.6 ± 23.2
SD1/SD2	0.59 ± 0.25	0.44 ± 0.13	0.45 ± 0.16	0.50 ± 0.11

RMSSD, square root of the mean squared differences of successive normal-to-normal intervals; pNN50, proportion of the number of interval differences of successive intervals greater than 50 ms; SD1, standard deviation of the points perpendicular to the line-of-identity in the Poincaré plot; SD2, standard deviation of the points along the line-of-identity in the Poincaré plot. The areas of the spectral peaks of very low frequency (VLF), low frequency (LF) and high frequency (HF) components are expressed in percentage (%) and normalized units (nu). Significant differences ($P < 0.05$) between hypoxic and normoxic conditions for each artificial hypoxia system are indicated by an asterisk (*).

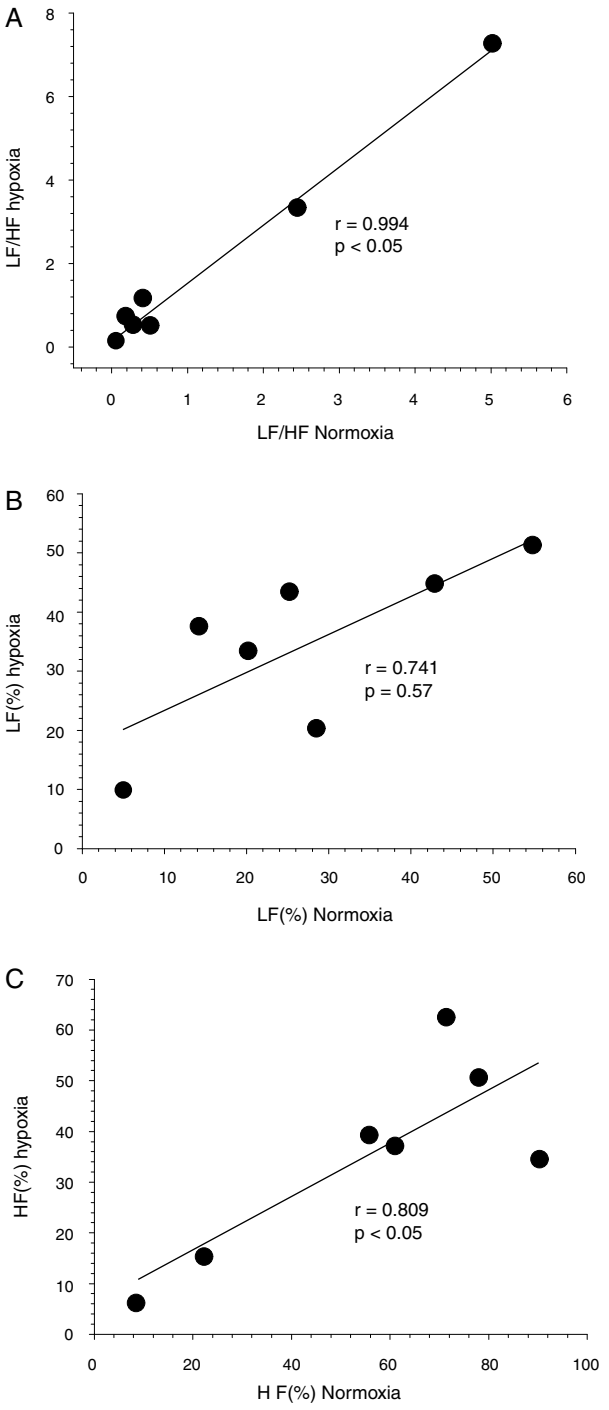

Figure 2 Correlation between normoxia and hypobaric hypoxia conditions for the parameters: LF/HF ratio (A), LF% (B) and HF% (C) in normoxia and HH condition.

Although we did not measure it, environmental pCO_2 could have been higher in NH than in HH. The difference may have been determined by the geometrical designs and fresh air renewal rates of the two hypoxic systems used, since the hypoxic tent has almost half the total volume of the hypobaric chamber (8 m^3 *versus* 15 m^3). Moreover, if gas flow is considered according to the technical data provided by the manufacturers, the difference is even higher: the hypoxic system attached to the tent supplies about 6–7 m^3 of gas mixture per hour, whereas the two vacuum pumps of the hypobaric chamber, working simultaneously, extract air at about 300 m^3 per hour.

Many authors have described a rise in the sympathetic tone or a vagal withdrawal in response to acute exposure to hypoxia at rest.[17,19,29–31] The data obtained in our study also reflected these responses by means of a rise in LFnorm and LF/HF ratio and a decrease in HF% and HFnorm under HH exposure (Table 2). Remarkably, these changes were not observed under NH exposure (Table 2), even though both altitude systems caused a significant decrease in SpO_2 when compared to normoxic values (Table 1). The absence of changes in HRV at NH conditions at rest confirms previous findings,[32] reporting no changes at a simulated altitude of 3500 m, but contrasts with another recent study describing changes in HF power at 4800 m above sea level.[19] The level of simulated altitude exposure could be an important factor affecting these differences, since in NH exposure a threshold of around 10% O_2 (the subjects in our study were submitted to an equivalent of 14% O_2) is considered necessary to achieve discernible modifications of muscle sympathetic nerve activity,[33] a parameter that correlates closely with some HRV indices.[34] Apart from these differences in HRV, another finding showed discordance between the two simulated altitude systems used in this study: the correlation between the areas of the spectral peaks (LF%, HF% and the LF/HF ratio) in normoxia and in HH (Fig. 2) was not observed when the subjects were submitted to NH, demonstrating that subjects with higher sympathetic modulation in normoxia maintained this condition during HH, but not during NH exposure. These two findings showed different behaviour of HRV in the two hypoxic conditions, which supports the hypothesis that, for the same simulated altitude of 3000 m a.s.l., NH and HH are not equal stimuli to the cardiovascular and respiratory systems, and probably affects also in a different way the psychoemotional status and the behaviour of the subjects. Our findings on this different HRV behaviour between the two simulated altitude systems corroborate previous studies that reported different cardioventilatory responses between HH and NH exposures.[35–37] In addition, since HRV is also sensitive to psycho-emotional factors,[27–29,38] differences in comfort and environmental conditions between HH and NH may have affected the differences here reported.

Correlation between HRV measurements in normoxia and SpO_2 in exercise at HH

The reduced partial pressure of oxygen at altitude causes the arterial oxygen saturation in the blood to decrease.[39] Burstcher et al.,[18] after reviewing the PubMed database from 1976 to 2007, concluded that arterial oxygen saturation values, determined 20–30 min after exposure to hypoxia equivalent to 2300–4200 m, were the most useful predictors of AMS susceptibility. Furthermore, exercise accelerates and increases the severity of AMS, which is associated with the greater arterial hypoxemia that takes place during exercise at high altitude.[40] In addition, acute hypoxia is a potent activator of the sympathetic nervous system in at least two ways. It causes relaxation of the vascular smooth muscle of the systemic circulation, which leads to hypotension

that activates baroreceptor mediation in order to maintain homeostasis. The other way is through stimulation of pulmonary arterial baroreceptors in order to reduce the pulmonary hypertension elicited by the hypoxic stimulus.[41] As mentioned above, this sympathetic activation is reflected in changes in some HRV parameters under HH. An inverse relationship between sympathetic nerve activity and arterial SpO_2 in subjects with and without history of high altitude pulmonary oedema has been observed.[42] Sympathetic nerve activity was also directly related to pulmonary artery pressure. Even though this study was conducted under different conditions (after 24–36 h of staying at 4559 m above sea level), the relationship between sympathetic activity and SpO_2 remains important. The different slope of this relationship can be justified by the time course of events: on reaching high altitude, a high sympathetic tone may be beneficial in order to activate homeostatic mechanisms. As the subject acclimatizes to the hypoxic environment and other physiological adjustments are on the go, a high sympathetic tone is no longer beneficial, and it needs to decline to conserve a physiological response and to maintain adequate SpO_2.

Here we report a significant correlation between sympathetic and vagal modulation in normoxia and SpO_2 at exercise in HH (Fig. 1). Individuals with higher sympathetic modulation (LF%) in normoxia had higher SpO_2 at exercise in HH (Fig. 1A) and individuals with higher vagal modulation (HF%) in normoxia showed lower SpO_2 in exercise at HH (Fig. 1B). Since correlations in LH%, HF% and LF/HF ratio between normoxia and HH conditions were also found (Fig. 2), we hypothesize that the evaluation of HRV in normoxia is a good predictor of the capacity of each subject to altitude acclimation. Some recent studies support this idea. A positive correlation between SpO_2 and LF power at high altitude, in unacclimatized subjects in rapid ascent to 3456 m has been reported[43] and Chen et al.[17] found that, after a rapid ascent to 3180 m, the unacclimatized healthy subjects that suffered AMS had more discordant changes in their HRV variables at high altitude than those subjects that did not show AMS. These findings indicate that the study of HRV could be a useful tool for evaluating the varying capacity of acute hypobaric hypoxia adaptation.

There are broad differences between individuals in the several physiological changes that occur in people when they ascend to high altitude, revealing individual differences in the tolerance to hypoxia and/or the ability to acclimatize.[39,18] Unfortunately, current research does not offer any test for ascertaining individual tolerance to hypoxia induced by altitude exposure that could be widely and easily used. The final objectives of the test should be to predict the potential capacity of each subject for altitude acclimation and to develop physical exercise under hypoxic conditions, in order to select people for altitude work according to risk criteria and to take the appropriate preventive measures. For optimal and wide application, this test should be based on the non-invasive recording of physiological changes induced by acute hypobaric exposure. We believe that the correlation that we found between HRV measured in normoxia and SpO_2 measured in HH opens up the possibility of using this tool in the prediction of tolerance to acute altitude exposure.

On the other hand, the use of hypoxia exposure as a complementary tool for athlete training must be carefully evaluated. According to our results, hypobaric and normobaric systems are different stimuli, at least as usually applied, probably eliciting a higher degree of variability in physiological responses to altitude acclimation in humans.

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Conflicts of interest

The authors have no conflicts of interest to declare.

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