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Physiological characteristics of elite high-altitude climbers

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Factors underlying the amplitude of exercise performance reduction at altitude and the development of high-altitude illnesses are not completely understood. To better describe these mechanisms, we assessed cardiorespiratory and tissue oxygenation responses to hypoxia in elite high-altitude climbers. Eleven high-altitude climbers were matched with 11 non-climber trained controls according to gender, age, and fitness level (maximal oxygen consumption, VO_{2max}). Subjects performed two maximal incremental cycling tests, in normoxia and in hypoxia (inspiratory oxygen fraction: 0.12). Cardiorespiratory measurements and tissue (cerebral and muscle) oxygenation were assessed continuously. Hypoxic ventilatory and cardiac responses were determined at rest and during exercise; hypercapnic ventilatory response was determined at rest. In hypoxia, climbers exhibited similar reductions to controls in VO_{2max} (climbers −39 ± 7% vs controls −39 ± 9%), maximal power output (−27 ± 5% vs −26 ± 4%), and arterial oxygen saturation (SpO_2). However, climbers had lower hypoxic ventilatory response during exercise (1.7 ± 0.5 vs 2.6 ± 0.7 L/min/%; $P < 0.05$) and lower hypercapnic ventilatory response (1.8 ± 1.4 vs 3.8 ± 2.5 mL/min/mmHg; $P < 0.05$). Finally, climbers exhibited slower breathing frequency, larger tidal volume and larger muscle oxygenation index. These results suggest that elite climbers show some specific ventilatory and muscular responses to hypoxia possibly because of genetic factors or adaptation to frequent high-altitude climbing.

Hypoxic exposure induces reduction in maximal exercise performance and maximal oxygen uptake (VO_{2max}; Gore et al., 1996; Wehrlin & Hallen, 2006; Chapman, 2013). After several hours at high altitude, symptoms of high-altitude illness such as acute mountain sickness (AMS) may also develop (Bartsch & Swenson, 2013). Significant interindividual differences have been reported regarding the amplitude of exercise performance reduction in hypoxia (Chapman, 2013) as well as the development of AMS (Bartsch & Swenson, 2013).

Higher arterial pulse oxygenation (SpO_2) during hypoxic exposure at rest (Roach et al., 1998; Burtscher et al., 2004; Faulhaber et al., 2014) and larger hypoxic ventilatory response (HVR) either at rest or during exercise (Moore et al., 1986; Richalet et al., 1988, 2012) might characterize individuals with low AMS susceptibility, although this is not a universal finding (Milledge et al., 1991; Hohenhaus et al., 1995; Bartsch et al., 2002). The ability to maintain VO_{2max} and performance at altitude is linked to the ability to defend SpO_2 (Chapman et al., 1999; Lazio et al., 2010). Endurance athletes with exercise-induced hypoxemia in normoxia have larger decline in VO_{2max} and endurance performance in hypoxic conditions compared with non-hypoxemic athletes (Lawler et al., 1988; Chapman et al., 2011). Lower exercise HVR, expiratory flow limitation, and impaired pulmonary gas exchange are potential mechanisms explaining the larger hypoxia-induced reduction in exercise performance (Chapman, 2013).

To understand the individual physiological characteristics leading to better preservation of maximal exercise performance in hypoxia and smaller sensitivity to AMS, investigating the physiological characteristics of elite high-altitude climbers is an attractive challenge. Only a few studies described their characteristics. In the 1980s, studies about extreme-altitude climbers suggested that successful climbers at extreme altitude exhibit larger HVR at rest during acute and prolonged hypoxic exposure (Schoene et al., 1984; Masuyama et al., 1986). In elite climbers, Oelz et al. (1986) reported resting hyperventilation both in normoxia and acute hypoxia resulting in higher SpO_2 in hypoxia. Conversely, Bernardi et al. (2006) reported that elite climbers reaching 8000-m summits (Everest and K2) without supplemental oxygen

displayed lower ventilatory sensitivity during hypoxic exposure than climbers failing to reach the summit or needing oxygen supplementation. These contrasting results may be due to different states of subjects' acclimatization and the severity of hypoxic exposure. Therefore, the specific physiological characteristics of elite high-altitude climbers remain to be elucidated and could provide important insights regarding the factors leading to better exercise performance preservation at altitude and low-altitude sickness sensitivity.

The aim of this study was to assess cardiorespiratory responses to acute hypoxic exposure in elite high-altitude climbers. In addition, while SpO_2 is generally used to characterize hypoxic stress, we also evaluated cerebral and muscle oxygenation at rest and during exercise in hypoxia with near-infrared resonance spectroscopy (NIRS) as reduced tissue oxygenation may be an important factor underlying exercise limitation under hypoxic conditions (Verges et al., 2012). We hypothesized that elite climbers may have greater hypoxic cardiorespiratory responses and better preservation of arterial and tissue oxygenation in hypoxia compared with non-climber trained individuals.

Methods

Subjects

Eleven high-altitude climbers were matched with 11 control subjects according to gender, age, and fitness level (maximal oxygen consumption, VO_{2max}). Climbers were all members of the national high-altitude climbing team of the French Alpine Club (*Fédération Française des Clubs Alpins et de Montagne*). They all had an extensive experience (> 5 years) in high-altitude mountaineering. They all reached summits between 4500 and 6500 m. Their physical activities mostly consisted of rock climbing at low altitude (< 3000 m), ice climbing, ski-mountaineering, and mountaineering at high altitude (between 3000 and 5000 m). Climbers were frequently exposed to altitudes > 2000 m (81 ± 45 days per year) but they were not acclimatized to high altitude at the time of the tests (no sojourn above 2000 m over the past 2 months). Control subjects were trained individuals performing running and cycling at low altitude (< 1000 m). All subjects lived at low altitude (< 1300 m) and were not acclimatized to high altitude. Subjects refrained from physical exercise on the 2 days prior to the tests, abstained from drinking caffeinated beverages on the test day, and had their last meal at least 2 h prior to the tests. All subjects were healthy and were not taking any medications during the study. The study was approved by the local ethics committee and performed according to the Declaration of Helsinki. Subjects were fully informed of the procedure and risks involved and gave their written consent.

Experimental design

First, a maximal incremental cycling test was performed in normoxia. Subjects exercised on a computer-controlled electrically braked cycle ergometer (Ergometrics 800, Ergoline, Bitz, Germany) with breath-by-breath gas analysis and electrocardiogram (Medisoft, Dinant, Belgium). After a 2-min resting period, subjects started cycling at 90 W (males) or 60 W (females) for 3 min, followed by 15 W (males) or 10 W (females) increments every minute until volitional exhaustion. After a 30-min resting period, hypercapnic normoxic and isocapnic hypoxic cardiorespiratory responses, as well as tissue oxygenation response, were measured at rest. After breathing ambient air for 5 min, subjects inhaled a normoxic hypercapnic gas mixture (inspiratory oxygen fraction, $FiO_2 = 0.21$; inspiratory carbon dioxide fraction, $FiCO_2 = 0.05$) for 5 min, then ambient air for 5 min and then an isocapnic hypoxic gas mixture ($FiO_2 = 0.12$, $FiCO_2$ adjusted to maintain end-tidal partial CO_2 pressure, $PetCO_2$, similar to the value recorded at the end of the ambient air period). Gas mixtures were delivered by an IsoCap-Altitrainer 200® (SMTEC, Nyon, Switzerland) via a face mask. One hour after the end of the normoxic exercise test, a second maximal incremental test was performed in hypoxia. Subjects inhaled the gas mixture ($FiO_2 = 0.12$) delivered by the IsoCap-Altitrainer 200® via a face mask. After a 2-min resting period, subjects started cycling at 60 W (males) or 30 W (females) for 3 min, followed by 15 W (males) or 10 W (females) increments every minute until volitional exhaustion.

Measurements

Cardiorespiratory measurements

Minute ventilation (VE), breathing pattern, gas exchanges, and heart rate (HR) were measured continuously breath-by-breath. SpO_2 was measured continuously by pulse oximetry (Masimo Radical 7, Masimo Corp., Irvine, California, USA). Blood lactate concentration at exhaustion (Lactate Plus, Nova Biomedical Corporation, Waltham, Massachusetts, USA) was determined during each exercise test.

Near-infrared resonance spectroscopy (NIRS)

Oxy[HbO_2]-, deoxy[HHb]-, and total[HbTot]-haemoglobin concentration changes and tissue oxygenation index (TSI) were estimated throughout testing sessions over multiple sites using a two-wavelength (780 and 850 nm) multichannel, continuous wave NIRS system (Oxymon MkIII, Artinis Medical Systems, Elst, the Netherlands). Quadriceps muscle hemodynamic was assessed from the left vastus lateralis using a 4-cm interoptodes distance. A probe holder was secured to the skin using double-sided tape and covered with a black sweatband to shield the optodes from ambient light. The left prefrontal cortex hemodynamic was assessed between Fp1 and F3 locations according to the international 10–20 EEG system with 3.5-cm interoptodes distance. The probe holder was secured to the skin with double-sided tape and maintained with Velcro headbands. Data were recorded continuously at 10 Hz and filtered with a 3-s width moving Gaussian smoothing algorithm before analysis. HbO_2, HHb and HbTot concentrations, and TSI are calculated as delta from the previous normoxic period in the hypercapnic and hypoxic response test and delta from the rest period during the exercise tests.

Sensations

Dyspnea and leg fatigue were assessed every 2 min with a standard 100-mm visual analog scale.

More information on materials and methods can be found in the online supplement.

Data analysis

Cardiorespiratory and NIRS data were averaged over the last 20 s of each step during exercise and over the last 30 s of each period during the hypercapnic and hypoxic test. To compare normoxic and hypoxic exercise tests at iso-power output and at exhaustion,

values corresponding to rest, 25% and 50% of the maximal normoxic power output (25%N and 50%N), 100% of the hypoxic workload (Exh H) and 100% of the normoxic power output (Exh N) were analyzed. The hypoxic ventilatory response at rest (during the resting hypoxic response test) and during the exercise test (at rest, 25%N, 50%N, ExhH) was calculated as follows (Richalet et al., 2012):

$$\left(VE_{hypoxia} - VE_{normoxia}\right)/\left(SpO_{2,normoxia} - SpO_{2,hypoxia}\right)$$

The hypoxic cardiac response at rest (during the resting hypoxic response test) and during the exercise test (at rest, 25%N, 50%N, ExhH) was calculated as follows (Richalet et al., 2012):

$$\left(HR_{hypoxia} - HR_{normoxia}\right)/\left(SpO_{2,normoxia} - SpO_{2,hypoxia}\right)$$

The hypercapnic ventilatory response during the resting hypercapnic response test was calculated as follows:

$$\left(VE_{hypercapnia} - VE_{normocapnia}\right)/\left(PetCO_{2,hypercapnia} - PetCO_{2,normocapnia}\right)$$

Statistical analysis

All statistical procedures were completed on Statistica version 10 (Statsoft, Tulsa, Oklahoma, USA). Normality of distribution and homogeneity of variances of the main variables were confirmed using a Skewness–Kurtosis normality test and the Levene's test, respectively. Two-way analysis of variance (ANOVA) (group × condition) with repeated measures was performed for maximum power output, VO_{2max} and blood lactate concentration at exhaustion. Three-way ANOVA (group × condition × time) with repeated measures was performed for cardiorespiratory parameters, sensations and NIRS data measured during exercise. Post-hoc Tukey's tests were applied to determine a difference between two mean values if the ANOVA revealed a significant main effect or interaction effect. Correlations were performed using linear regression and Pearson's coefficient. For all statistical analyses, a two-tailed alpha level of 0.05 was used as the cut-off for significance. All data are presented as mean values ± SD.

Results

Climbers and controls had similar anthropometric characteristics, lived at similar altitude level and had similar normoxic VO_{2max} (Table 1).

Normoxic and hypoxic exercise tests

Table 2 and Fig. 1 show normoxic and hypoxic cardiorespiratory responses during exercise in climbers and controls. Similar reductions from normoxia to hypoxia in both groups were observed for maximal power output (climbers −27 ± 5% vs controls −26 ± 4%; $P > 0.05$) and VO_{2max} (climbers −39 ± 7% vs controls −39 ± 9%; $P > 0.05$). Submaximal and maximal minute ventilation, inspiratory duty cycle, heart rate, and SpO_2 were similar between climbers and controls. Breathing pattern showed significant difference between climbers and controls (Fig. 1). A significant group main effect was obtained for both breathing frequency (FR; $F = 6.1$, $P = 0.03$) and tidal volume (VT; $F = 6.2$, $P = 0.03$) while a significant group × condition × time interaction was obtained for breathing frequency ($F = 4.4$, $P = 0.01$). FR was larger in controls compared with climbers while VT was larger in climbers compared with controls. In addition, controls at ExhH in hypoxia had larger FR compared with climbers. Significant group main effect ($F = 7.8$, $P = 0.02$) and group × time interaction ($F = 3.3$, $P = 0.03$) were obtained for hypoxic ventilatory response that was significantly larger at ExhH in controls compared with climbers (Fig. 2). No difference in hypoxic cardiac response was observed between groups (results not shown).

A significant main group effect was obtained for dyspnea ($F = 5.6$, $P = 0.04$) and leg fatigue ($F = 5.3$, $P = 0.04$) while a significant group × time × condition interaction was obtained for dyspnea only ($F = 8.0$, $P = 0.003$). Dyspnea was greater in climbers compared with controls in normoxia at 50%N and Exh N only.

No difference in blood lactate concentration at exhaustion was found between climbers and controls both in normoxia (13.5 ± 2.6 vs 12.5 ± 3.5 mmol/L, $P > 0.05$) and in hypoxia (13.9 ± 3.5 vs 12.4 ± 3.0 mmol/L, $P > 0.05$).

NIRS data during exercise are shown in Table 3. Significant group × time × condition interaction ($F = 14.2$, $P < 0.001$) were obtained for muscle TSI. Climbers had significantly larger muscle TSI at 50%N in hypoxia and at ExhH in normoxia. All other NIRS variables did not differ between groups.

Table 1. Subjects' characteristics

	Climbers $n = 11$	Controls $n = 11$
Number of females/males	3/8	3/8
Age (years)	25 (2)	24 (4)
Height (cm)	174 (8)	173 (7)
Weight (kg)	66 (9)	65.7 (7)
Residential altitude (m)	643 (465)	314 (128)
VO_{2max} (mL/min/kg)	53.3 (4.6)	51.7 (8.1)

Data are means (SD). VO_{2max}, sea level maximal oxygen consumption.

Resting hypercapnic and hypoxic test

Figure 3 shows the hypercapnic ventilatory response at rest. Hypercapnic ventilatory response was smaller in climbers compared with controls (climbers 1.8 ± 1.4 vs controls 3.8 ± 2.5 mL/min/mmHg; $P < 0.05$). No difference in HVR at rest was observed between groups (results not shown). All other cardiorespiratory parameters did not differ between groups in hypercapnia nor in hypoxia between groups (results not shown). NIRS variables did not differ between groups (results not shown).

Correlations

Positive correlations between changes from normoxia to hypoxia in maximal power output and SpO_2 at rest

Table 2. Cardiorespiratory responses and sensations during exercise

			Rest	25%N	50%N	Exh H	Exh N
Power output (W)	Climb		0	83 (15)	151 (29)	216 (36)	298 (57)
	Con		0	85 (16)	152 (27)	219 (35)	299 (57)
SpO_2 (%)	Climb	N	98 (1)	98 (1)	97 (1)	97 (1)	96 (2)
		H	86 (5)	73 (7)	69 (7)	68 (6)	NA
	Con	N	97 (1)	97 (1)	97 (1)	96 (1)	96 (2)
		H	85 (5)	75 (5)	73 (6)	72 (7)	NA
$PetCO_2$ (mmHg)	Climb	N	34.0 (2.0)	42.0 (3.5)	43.3 (4.3)	42.2 (4.3)	34.0 (3.3)
		H	33.2 (1.9)	34.9 (2.4)	33.4 (2.4)	28.7 (2.2)	NA
	Con	N	36.5 (3.7)	41.1 (2.1)	41.8 (1.4)	41.6 (2.2)	31.1 (1.8)
		H	34.4 (3.3)	35.6 (2.7)	33.4 (2.8)	27.4 (1.4)	NA
Ti/Ttot	Climb	N	0.40 (0.06)	0.44 (0.03)	0.45 (0.03)	0.45 (0.03)	0.48 (0.02)
		H	0.39 (0.10)	0.42 (0.07)	0.45 (0.03)	0.47 (0.02)	NA
	Con	N	0.39 (0.05)	0.43 (0.03)	0.44 (0.03)	0.46 (0.03)	0.49 (0.02)
		H	0.40 (0.04)	0.44 (0.03)	0.46 (0.03)	0.49 (0.02)	NA
HR (/min)	Climb	N	73 (11)	114 (13)	145 (12)	171 (15)	192 (11)
		H	93 (15)	145 (12)	169 (10)	184 (10)	NA
	Con	N	65 (13)	109 (11)	136 (12)	163 (11)	186 (11)
		H	88 (17)	136 (13)	160 (12)	177 (10)	NA
Dyspnea	Climb	N	0.1 (0.4)	1.1 (0.9)	3.2 (1.5)*	6.2 (1.8)*	9.7 (0.6)
		H	0.6 (1.0)	3.5 (1.7)	7.0 (1.4)	9.5 (0.7)	NA
	Con	N	0.0 (0.0)	0.5 (1.0)	1.7 (1.5)	4.2 (1.7)	9.1 (1.3)
		H	0.2 (0.5)	2.6 (1.3)	5.7 (1.7)	9.7 (0.6)	NA
Leg fatigue	Climb	N	0.0 (0.0)	1.0 (1.0)	3.4 (1.7)*	6.3 (1.7)*	9.7 (0.6)
		H	1.0 (1.5)	3.7 (1.5)	7.3 (1.3)	9.6 (0.7)	NA
	Con	N	0.0 (0.0)	0.4 (0.7)	1.8 (1.4)	4.7 (1.5)	9.0 (1.6)
		H	0.6 (1.0)	2.9 (1.5)	6.1 (1.7)	9.7 (0.6)	NA

Data are means (SD).*Significant difference between groups ($P < 0.05$).Con, controls; Climb, climbers; N, normoxia; H, hypoxia; 25%N and 50%N, variables at 25% and 50% of the maximal normoxic power output; Exh H, variables at maximal hypoxic power output; Exh N, variables at maximal normoxic power output; SpO_2, arterial pulse oxygen saturation; $PetCO_2$, end-tidal CO_2 pressure; Ti/Ttot, inspiratory duty cycle; HR, heart rate; NA, variables not available at this power output in hypoxia.

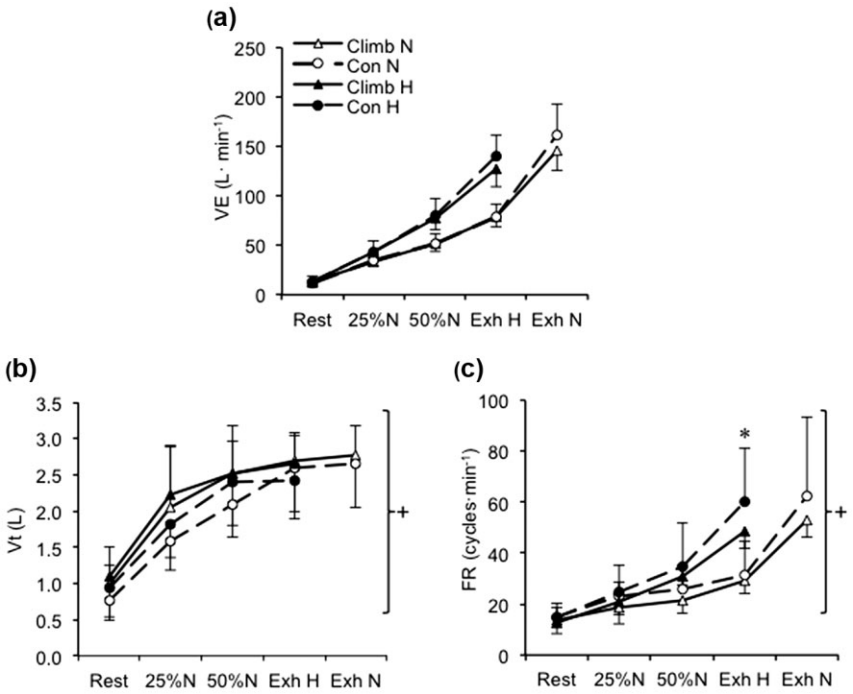

Fig. 1. Minute ventilation (a) and breathing pattern (b,c) during exercise in normoxia and hypoxia. Con, controls; Climb, climbers; N, normoxia; H, hypoxia; 25%N and 50%N, 25% and 50% of the maximal normoxic power output; Exh H, power output at exhaustion in hypoxia; Exh N, power output at exhaustion in normoxia; VE, minute ventilation; Vt, tidal volume; FR, breathing frequency. *Significant difference between groups ($P < 0.05$); $^{+}$significant group main effect ($P < 0.05$).

($r = 0.44$, $P < 0.05$), 25%N ($r = 0.65$, $P < 0.05$) and 50%N ($r = 0.62$, $P < 0.05$) were observed. No correlation between changes from normoxia to hypoxia in maximal power output and hypoxic or hypercapnic ventilatory responses was observed. Neither hypercapnic nor hypoxic ventilatory responses nor NIRS variables correlated with ventilation and breathing pattern in normoxia and hypoxia (results not shown).

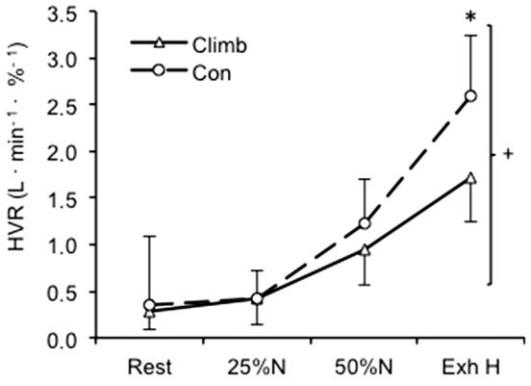

Fig. 2. Hypoxic ventilatory response during exercise. HVR, hypoxic ventilatory response; see Fig. 1 for other abbreviations. *Significant difference between groups ($P < 0.05$); $^{+}$significant group main effect ($P < 0.05$).

Discussion

This study aims to identify the cardiorespiratory and tissue oxygenation responses to hypoxia in elite high-altitude climbers compared with non-climber trained individuals. Compared with control individuals, climbers exhibited: (i) similar hypoxia-induced reductions in VO_{2max} and maximal power output; (ii) similar SpO_2 reduction in hypoxia both at rest and during exercise; (iii) lower hypoxic ventilatory response during exercise and hypercapnic ventilatory response at rest; (iv) slower and deeper breathing pattern during exercise; and (v) larger muscle oxygenation index during exercise. These results suggest that elite climbers show some specific ventilatory responses to hypoxia that might confer advantages for climbing at high altitude.

Normoxic VO_{2max} values in climbers in the present study are similar to previous reports in elite climbers (Richalet et al., 1988) but slightly lower than values from six world-class high-altitude climbers (Oelz et al.,

Table 3. Cerebral and muscle NIRS variables during exercise

			25%N	50%N	Exh H	Exh N
ΔQ-HbO_2 (μmol/L)	Climb	N	–3.7 (3.9)	–4.1 (4.4)	–4.8 (3.6)	–11.1 (4.1)
		H	–9.8 (6.2)	–13.3 (8.2)	–20.5 (6.6)	NA
	Con	N	–3.1 (2.9)	–4.2 (3.7)	–6.3 (6.3)	–8.9 (7.0)
		H	–11.8 (5.8)	–15.5 (7.9)	–18.5 (8.6)	NA
ΔQ-HHb (μmol/L)	Climb	N	–0.1 (4.6)	4.3 (7.4)	7.8 (9.2)	10.7 (11.0)
		H	5.8 (6.2)	9.5 (8.7)	15.9 (9.3)	NA
	Con	N	–0.6 (6.3)	4.1 (8.2)	10.1 (12.1)	12.1 (14.0)
		H	8.4 (8.7)	14.1 (11.4)	17.7 (14.3)	NA
ΔQ-HbTot (μmol/L)	Climb	N	–3.8 (6.6)	0.1 (6.3)	2.9 (11.3)	–0.3 (11.3)
		H	–4.0 (6.1)	–3.8 (5.4)	–4.6 (7.1)	NA
	Con	N	–3.7 (5.6)	–0.1 (5.9)	3.8 (8.1)	3.2 (11.2)
		H	–3.3 (5.6)	–1.4 (5.8)	–0.8 (8.2)	NA
ΔQ-TSI (%)	Climb	N	–1.5 (3.6)	–5.0 (5.7)	–6.2 (6.2)*	–10.7 (8.4)
		H	–8.8 (5.1)	–11.9 (6.7)*	–18.5 (9.0)	NA
	Con	N	1.2 (7.2)	–6.0 (8.5)	–12.5 (12.8)	–13.7 (11.8)
		H	–11.6 (7.6)	–16.5 (8.7)	–18.3 (8.2)	NA
ΔPFC-HbO_2 (μmol/L)	Climb	N	0.8 (2.5)	5.1 (3.3)	8.0 (3.5)	6.9 (3.7)
		H	–1.4 (3.3)	0.1 (5.3)	–3.3 (6.5)	NA
	Con	N	0.0 (1.7)	2.7 (2.5)	7.6 (3.9)	7.8 (5.5)
		H	–3.0 (2.9)	–3.0 (3.9)	–5.7 (6.4)	NA
ΔPFC-HHb (μmol/L)	Climb	N	0.2 (1.0)	0.0 (1.8)	1.1 (1.4)	4.9 (2.4)
		H	3.3 (2.3)	6.5 (3.2)	9.4 (3.4)	NA
	Con	N	0.4 (1.0)	0.0 (1.2)	1.7 (2.0)	6.4 (3.1)
		H	3.4 (1.5)	5.7 (1.9)	8.3 (3.0)	NA
ΔPFC-HbTot (μmol/L)	Climb	N	1.0 (2.1)	5.1 (3.0)	9.1 (2.8)	11.7 (4.7)
		H	1.9 (2.1)	6.6 (4.5)	6.2 (8.0)	NA
	Con	N	0.4 (1.3)	2.8 (2.2)	13.5 (4.6)	13.5 (4.6)
		H	0.4 (2.0)	2.7 (3.2)	2.6 (8.1)	NA
ΔPFC-TSI (%)	Climb	N	1.4 (2.0)	0.7 (3.9)	–3.2 (5.4)	–11.3 (8.1)
		H	–3.1 (3.9)	–5.6 (5.5)	–15.4 (17.7)	NA
	Con	N	0.4 (1.6)	0.6 (2.3)	–2.0 (2.7)	–11.4 (8.2)
		H	–4.7 (2.5)	–8.8 (4.2)	–17.5 (12.4)	NA

Data are mean (SD) delta from rest.*Significant difference between groups ($P < 0.05$).Con, controls; Climb, climbers; N, normoxia; H, hypoxia; 25%N and 50%N, variables at 25% and 50% of the maximal normoxic power output; Exh H, variables at maximal hypoxic power output; Exh N, variables at maximal normoxic power output; PFC, prefrontal cortex; Q, quadriceps; HbO_2, oxyhemoglobin; HHb, deoxyhemoglobin; HbTot, total hemoglobin; NA, variables not available at this power output in hypoxia; NIRS, near-infrared resonance spectroscopy.

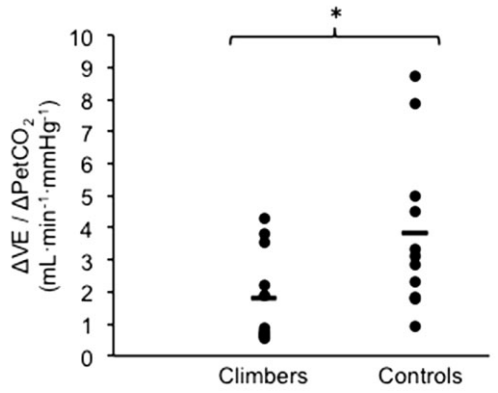

Fig. 3. Hypercapnic ventilatory response at rest. ΔVE, changes in minute ventilation from normocapnia to hypercapnia; $\Delta PetCO_2$, changes in end-tidal CO_2 partial pressure from normocapnia to hypercapnia. *Significant difference between groups ($P < 0.05$).

1986). The difference between the later and the present studies might arise from age difference (younger climbers in the present study), distinct expertise [in Oelz et al. subjects were elite extreme altitude (> 8000 m) climbers], or type of training (climbers from the present study performed a significant amount of rock climbing and possibly less endurance activities compared with other climber populations). This is the first study to compare elite climbers with non-climber trained athletes paired for VO_{2max}. In order to determine the specific physiological profile of elite climbers, it is important to compare them to controls individuals of similar VO_{2max} because of the well-known effect of maximal aerobic capacity on exercise hypoxic responses (Lawler et al., 1988; Gore et al., 1996; Mollard et al., 2007b; Faiss et al., 2014). The amplitude of reduction in maximal power output and VO_{2max} observed in the present study when FiO_2 was reduced to 0.12 is consistent with studies using similar levels of hypoxia in trained individuals (Subudhi et al., 2007; Rupp et al., 2013). Despite their great ability to climb at high altitude, elite climbers showed similar reductions in maximal power output and VO_{2max} in hypoxia compared with controls. Hence, their performance at high altitude may not be underlined by greater preservation of maximal aerobic capacity, at least when measured during cycling. Climbing at high altitude requires abilities and skills other than maximal aerobic capacity. It has been suggested for instance that elite climbers exhibit a lower metabolic cost for climbing at high altitude (Billat et al., 2010).

Previous studies having measured reduction in SpO_2 in elite climbers compared with non-climber active individuals during acute hypoxic exposure (Richalet et al., 1988) or less successful elite climbers (i.e., not reaching 8000-m summits without oxygen supplementation) during prolonged high-altitude exposure (Bernardi et al., 2006) did not report differences between groups. Conversely, Oelz et al. (1986) reported lower SpO_2 reduction in a small group of elite climbers ($n = 6$) vs control untrained subjects ($n = 3$) during acute hypoxic exposure at rest. Based on the present results, the reduction in inspired oxygen pressure appeared to translate into similar reduction in arterial blood oxygenation during acute hypoxic exposure in both elite climbers and control subjects paired for VO_{2max}. Interestingly, at tissue level, while hypoxia-induced prefrontal deoxygenation was similar in both groups, quadriceps oxygenation during exercise was larger in climbers compared with controls, both in normoxia and hypoxia. The smaller reduction in quadriceps TSI during exercise in elite climbers may be interpreted as a greater O_2 delivery to the muscle or a smaller muscle oxygen extraction. Exercise training in hypoxia has been suggested to improve muscle responses to exercise (Hoppeler et al., 2008), including metabolism and efficiency, although these results remain controversial (Robach et al., 2014). Hence, because elite climbers frequently trained under hypoxic conditions, they may exhibit some specific muscular or vascular adaptations which require further evaluation.

When combining data from both groups, significant positive correlations were observed between changes from normoxia to hypoxia in maximal power output and SpO_2 reduction at rest and during exercise. The role of SpO_2 reduction regarding maximal exercise performance decrement in hypoxia has been previously suggested based on similar correlations (Lawler et al., 1988; Chapman et al., 1999; Wehrlin & Hallen, 2006; Mollard et al., 2007a; Faiss et al., 2014). It seems that the ability to defend SpO_2 during hypoxic exercise may be a key mechanism regarding the amplitude of maximal exercise performance reduction. Hence, the similar reduction in SpO_2 during hypoxic exercise between elite climbers and controls may underlie their similar reduction in maximal exercise performance.

In the present study, in contrast with our hypothesis and previous reports (Schoene et al., 1984; Masuyama et al., 1986), elite climbers had lower HVR especially during high-intensity exercise (Fig. 2) compared with controls. This lower respiratory chemosensitivity is supported by the lower hypercapnic ventilatory response measured in climbers compared with controls (Fig. 3). These results may appear paradoxical based on previous results suggesting better acclimatization in subjects with larger HVR (Richalet et al., 2012). They may, however, corroborate the data from Bernardi et al. (2006) who reported lower minute ventilation without higher desaturation after 9 days at 5200 m in climbers who reached 8000-m summits without oxygen supplementation compared with climbers who did not reach the summit or needed supplemental oxygen. These authors proposed that lower HVR in successful elite climbers may suggest a better ventilatory efficiency and could allow these individuals to preserve a larger ventilatory reserve for extreme-altitude climbing. In ski

mountaineers, Faiss et al. (2014) reported a positive correlation between acute hypoxia-induced hyperventilation during exercise and VO_{2max} decrement, and suggested that an excessive increase in minute ventilation in hypoxia might be inefficient to preserve oxygenation and performance. Whether mechanisms such as improved oxygen pulmonary diffusion (Torre-Bueno et al., 1985; Calbet et al., 2003) may contribute to improve ventilatory efficiency in elite climbers as suggested by Bernardi et al. (2006) remains to be investigated.

Another remarkable result from the present study is the difference in breathing pattern observed in climbers compared with controls (Fig. 1). Slower and deeper breathing as observed in climbers may improve gas exchange (Bernardi et al., 2001; Keyl et al., 2003) and therefore enhance ventilatory efficiency. Similar to the present results, Bernardi et al. (2006) reported slower and slightly deeper breathing in successful elite climbers during prolonged high-altitude exposure. Hence, specific breathing pattern may be part of the physiological characteristics of elite climbers. Faulhaber et al. (2014) also reported that AMS susceptible subjects have a larger breathing frequency and lower tidal volume at rest in acute hypoxia compared with AMS non-susceptible subjects.

No difference was observed in hypoxic cardiac response either at rest or during exercise between climbers and controls. Previous studies also reported no difference in hypoxic cardiac response in successful elite climbers (Oelz et al., 1986; Bernardi et al., 2006). In the present study, climbers reported larger dyspnea and leg fatigue levels during exercise both in normoxia and hypoxia. This may relate to the fact that climbers did not perform cycling training as opposed to controls.

There are several limitations to the present study. Firstly, the fact that the two maximal exercise tests were performed 1 h apart might increase the amplitude of performance reduction and the physiological (e.g., ventilatory) responses in hypoxia because of fatigue due to the first test. However, it is unlikely to have influenced the outcomes of the present study as (i) the amplitude of performance reduction was similar compared with previous studies; and (ii) both climbers and controls performed exactly the same protocol. Secondly, the present results need to be confirmed with exercise tests (intensity, duration, modality) more representative to climbing and during prolonged high-altitude exposure. Thirdly, whether the differences observed between climbers and controls might be due to genetic factors or to adaptation to frequent high-altitude climbing remains to be elucidated. Despite the non-acclimatized state of the climbers (no sojourn above 2000 m over the past 2 months), they may exhibit sustained adaptations to regular training in a hypoxic environment. Finally, potential differences between male and female climbers need to be investigated.

In conclusion, elite climbers exhibit a similar reduction in maximal power output and VO_{2max} in hypoxia compared with non-climber controls with similar normoxic VO_{2max}, but lower hypoxic ventilatory response with a slower and deeper breathing pattern. In addition, NIRS index of better quadriceps oxygenation during exercise suggests some specific muscular adaptations possibly caused by exercise training in hypoxia. Hence, specific ventilatory and muscular responses to hypoxic exercise may characterize elite climbers.

Perspectives

Interindividual differences regarding altitude tolerance, in terms of exercise performance reduction and altitude illness, is a striking phenomenon (Martin et al., 2010). While some extraordinary individuals are able to reach summits above 8000 m without additional oxygen, others develop severe altitude illnesses such as life-threatening pulmonary or cerebral edema below 4000 m (Bartsch & Swenson, 2013). The mechanisms and individual phenotypes underlying tolerance to hypoxia at high altitude remain an important scientific quest that would have important implications not only for climbers, travelers and workers at altitude but also for pathological conditions with hypoxic stress. The present study describes some specific responses to hypoxic exercise in high-altitude elite climbers that may provide them benefits to perform in hypoxia (Bernardi et al., 2006). Future studies should confirm these results during climbing and high-altitude exposure and should consider additional factors including genetic profile (Hennis et al., 2015) in order to improve our understanding of how humans can adapt to hypoxia.

Key words: Exercise, hypoxia, acclimatization, ventilatory response.

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Supporting information

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Appendix S1. Materials and methods.