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# Cardiorespiratory response to exercise in elite Sherpa climbers transferred to sea level

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GARRIDO, EDUARDO; RODAS, GIL; JAVIERRE, CASIMIRO; SEGURA, RAMON; ESTRUCH, ASSUMPCIO; VENTURA, JOSEP L.

*CEARE, Center of High Performance and Exercise Physiology, and Department of Physiological Sciences and Nutrition, Medical School, University of Barcelona, Barcelona, SPAIN*

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Address for correspondence: Eduardo Garrido, M.D., CEARE, Secretaria General de l'Esport, Avda Països Catalans 12, 08950 Esplugues de Llobregat, Barcelona, Spain.

## ABSTRACT

Himalayan Sherpas are well known for their extraordinary adaptation to high altitude and some of them for their outstanding physical performance during ascents to the highest summits. To cast some light on this subject, we evaluated the cardiorespiratory response during exercise at sea level of six of the most acknowledged Sherpa climbers, mean age (±SD) 37 (±7) yr old. Continuous electrocardiogram and breath-by-breath pulmonary gas exchange until exhaustion were obtained by following the Bruce protocol. We detected a maximal oxygen uptake ($\cdot VO_{2max}$) of 66.7 (±3.7) $mL \cdot min^{-1} \cdot kg^{-1}$, maximal cardiac frequency of 199(±7) $beats \cdot min^{-1}$, and ventilatory anaerobic threshold at 62 (±4)% of $\cdot VO_{2max}$. These factors could help to explain the greater performance level shown by several elite climbers of this ethnic group. The high functional reserve demonstrated by this very select group of highlanders could be associated with natural selection and with special physiological adaptations probably induced by long-training in a hostile environment.

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The extraordinary adaptation and physical resistance that some highland ethnic groups present at high altitudes are widely acknowledged; and, without any doubt, the most prestigious example is that of the Sherpas, famous for their performance during ascents to the highest peaks of the world. This small ethnic group directly descended from Tibetans who settled in northeast Nepal some 500 yr ago within the abruptly orographical area around Mount Everest and *Cho-Oyu* in the south Himalayas at an altitude of between 3,000 and 4,900 m above sea level. Although the majority of Sherpas are farmers, it is the only Himalayan community to boast a notable number of individuals who participate in extreme-altitude expeditions and have earned worldwide recognition for their outstanding performance during ascents to the earth's highest summits.

Some studies have demonstrated the existence of physiological characteristics that would explain the excellent performance of native highlanders. It is well known that highland dwellers make greater use of glycidic substrates (13) and show a particular enzymatic adaptation that attenuates pyruvate to lactate flux (14). Likewise, they show better ventilatory efficiency (18), lower pulmonary resistance (10), and differences in the acid-base balance (20). However, other studies have not found any physiological or biochemical bases that could account for their superior performance. Apparently, their muscle capillary or mitochondrial volume density is not greater than those of lowland dwellers acclimatized to high altitude, nor indeed than those of sedentary individuals (17), showing low enzymatic activity in both the oxidative as well as glycolytic anaerobic pathways (12). Nevertheless, Moore et al. (23) suggested that the effectiveness of the oxygen transport system and uptake improves with successive generations exposed to high altitude hypoxia, and another report showed that Tibetan newborns had higher arterial oxygen saturation at birth and during the first months of life than Han Chinese newborns (24).

However, in the majority of the previous studies to evaluate functional capacity in Himalayan highlanders or Andean Amerindians, average values of·$VO_{2max}$ between 37 and 52 $mL·min^{-1}·kg^{-1}$ have been observed (5,13,17,21,27,34,38). It is noteworthy that the majority of studies performed on Himalayan natives have been carried out at high altitude, or using low-specific exercise tests, such as the bicycle ergometer for Sherpa natives (21,27), with the exception of the use of this ergometer for the north-Himalaya population groups, accustomed to cycling along the Tibetan plateau (34,38), or walking uphill test (31), or the step test (5,17). Another report showed results based on an indirect estimation of oxygen uptake (17). Likewise, it should also be pointed out that only two reports include natives with great experience in ascents at extremely high altitude (5,31), one of which was carried out with the collaboration of Tensing Norgay (31), the Sherpa famous for the first human conquest of Everest in 1953.

With the aim of defining the aerobic profile and functional reserve of some select individuals of this ethnic group, we proposed: 1) the study of an elite group of Sherpa climbers and evaluate their performance at sea level; 2) the application of an exercise test as specific as possible, and as close as possible to their usual physical activity in the mountains; and 3) the determination by means of direct methodology of certain cardiorespiratory parameters, including the noninvasive ventilatory threshold, hitherto unstudied in Himalayan highlanders.

## METHODS

**Subjects.** Six males selected from the 25 best Sherpa climbers on the basis of best climbing records and greatest number of ascents performed at extreme altitude. The subjects were 37 (±7) yr old. All of them were born and had spent practically all of their lives within the *Solu Khumbu* region of northeastern Nepal at an average altitude of 3,150(±650) m above sea level. Only one of them (subject 2) had recently spent periods of time at low altitude (1,300 m) in Kathmandu (Nepal) between alpine expeditions. The whole group had successfully completed, without the use of supplementary oxygen, a total of 67 ascents to above 7,000 m, 45 of which were above 8,000 m. They had reached 25 summits above that altitude, including the summit of Mt. Everest (8,848 m) on 12 occasions. Four subjects had recently climbed beyond 8,000 m (48 d before the study), and two of these had reached the summit of Mt. Everest. None of them had followed a physical training program, other than their usual participation in high-altitude expeditions once or twice a year. One of them (subject 3) also worked as a guide for a trekking agency when not participating in expeditions at extreme altitude. The present study was carried out coinciding with a company-sponsored visit of the Sherpa climbers to our country. The subjects were informed of the purpose and the experimental noninvasive procedures to which they all granted their consent in accordance with the Institutional Review Board. Previously, a medical history was taken (with the assessment of a native expert translator from the Nepal Consulate), and a routine physical examination was performed.

**Anthropometry.** Weight was determined using a scale with a precision of ± 0.1 kg (Seca, Soenhle, Germany), and height by means of a tape with a precision of ± 1 mm (Holtain Ltd., Crymych, UK). Skinfold thickness (triceps, subscapular, suprailiac, and quadriceps) was measured using a caliper with a precision of ±0.2 mm (Holtain Ltd.). Skeletal diameters (wrist and knee) were measured by means of a pachymeter with a precision of ± 0.01 mm (Mitutoyo, Tokyo, Japan). Limb circumferences(arm and calf) were measured using a metal spring-loaded tape (Holtain, Ltd.). The unilateral measurements were always taken on the right side, following the procedure proposed by Ross et al. (30). Body fat (% fat) was calculated according Durnin and Womersley (7).

**Stress test.** The study was carried out in a laboratory located at 125 m above sea level at a time when all the natives had been at low altitude(1,300 m or below) for only 2 wk. The room temperature ranged between 22 and 24°C, and the relative humidity between 55 and 65%. The subjects were asked to abstain from strenuous exercise during the 3 d before the test. The evaluation took place in the morning, 3 h after a light breakfast. A standard 12-lead electrocardiogram (Schwarzer Cardioscript CD-6000, Picker, Germany) was obtained with the subjects at rest.

Afterward, all subjects completed an exercise test on a treadmill(Laufergotest LE-6, Jaeger, Germany) under normoxic conditions until exhaustion; the Bruce protocol was followed (4). Pulmonary gas exchange was measured using a breath-by-breath automated gas analysis system (CPXII, MedGraphics, St. Paul, MN). The instrument was calibrated before each test, both in relation to volume and flow by means of a 3-L capacity syringe (Hans Rudolph, Kansas City, MO), and gases obtained from a tank (Medical Graphics Corp., Plumsteadville, PA) containing a reference mixture (5% CO2, 12% O2, balanced N2), and with atmospheric air (well-ventilated laboratory). The following parameters were recorded: pulmonary ventilation (·VE, $L \cdot min^{-1}$ BTPS), tidal volume(·VT, $mL \cdot min^{-1}$ BTPS), respiratory frequency (fR, $min^{-1}$), end-tidal $PCO_2$ ($PET_{CO2}$, mm Hg), end-tidal $PO_2$ ($PET_{O2}$, mm Hg), oxygen uptake (·$VO_2$, $mL \cdot min^{-1}$ STPD), and expired $CO_2$ (·$VCO_2$, $mL \cdot min^{-1}$ STPD). The following data were automatically calculated: respiratory quotient [R =(·$VCO_2$··$VO_2^{-1}$)], oxygen uptake relative to body mass (·$VO_2$, $ml \cdot min^{-1} \cdot kg^{-1}$ STPD), respiratory equivalent for oxygen (·VE··$VO_2^{-1}$), respiratory equivalent for carbon dioxide(·VE··$VCO_2^{-1}$), and energy expenditure expressed in metabolic units (MET). The different respiratory values were obtained from the average of the last 30 s of each stage and the same was done during exhaustion, rejecting the maximum peak values obtained. Continuous electrocardiogram (Simpliscriptor EK-31, Hellige, Germany) with instantaneous determination of cardiac frequency (fC) was obtained during the test by means of the CM5 precordial lead, and we chose the average fC of the last 15 s of each stage and during exhaustion. The maximum peak values were also rejected. Oxygen pulse was calculated as ·$VO_2 \cdot fC^{-1}$($mL \cdot beat^{-1}$). We estimated the anaerobic threshold (AT) by means of the noninvasive "V-Slope" ventilatory method proposed by Beaver et al. (3).

As the subjects had never experienced a medical exercise test before, before the test they were invited to walk on the treadmill for a few minutes wearing the mask, for them to become familiarized with the experimental procedure. Before starting the exercise protocol, the subjects remained at rest for 3 min connected to the gas analyzer with the aim of obtaining the optimal basal data and achieving equilibrium in the gas-exchange tubes.

## RESULTS

**Anthropometry.** Body mass was 59.4 (± 4) kg, height was 163.5 (± 5.2) cm, with mean body surface area equal to 1.6 (± 0.1) $m^2$, and mean body fat proportion equal to 11.9 (± 1.3)%. Wrist and knee skeletal diameters were equal to 5.5 (± 0.9) and 9.4(± 0.2) cm, respectively. Arm and calf limb circumferences were equal to 26.3 (± 1.2) and 33.9 (± 1.1) cm, respectively.

**Functional assessment.** Three subjects reached exhaustion point during the 2nd or 3rd min of the fifth stage, whereas the other three subjects completed this stage. We observed that the natives all showed an apparently deficient mechanical efficiency on the treadmill with a peculiar walking and running style. The average (30 s) data of the different respiratory variables obtained during maximal effort are shown in Table 1.Figure 1 shows the evolution of the ·VE,·$VO_2$, and fC throughout the exercise test. Table 2 shows individual data for ·$VO_{2max}$, maximal fC, percentage of·$VO_{2max}$ at ventilatory AT, and fC at ventilatory AT. Five subjects showed the ventilatory AT during the third stage of the protocol at an average·$VO_2$ of 2.56 (±0.38) L·$min^{-1}$ (43.4 ± 3.3 mL·$min^{-1}$·$kg^{-1}$). One of them (subject 5) showed an unclear ventilatory AT, which was difficult to determine with precision.

| Parameters | Maximal |
|---|---|
| VE (L·$min^{-1}$) | 134 ± 22.8 |
| VT (mL·$min^{-1}$) | 2994.7 ± 449.5 |
| fR ($min^{-1}$) | 45.2 ± 3.8 |
| $VCO_2$ (mL·$min^{-1}$) | 4741.8 ± 523.5 |
| $VO_2$/fC$^{-1}$ (mL·$beat^{-1}$) | 20.2 ± 2.6 |
| $PETO_2$ (mm Hg) | 124 ± 3 |
| $PETCO_2$ (mm Hg) | 41 ± 5 |
| VE·$VCO_2^{-1}$ | 28.1 ± 3.3 |
| VE·$VO_2^{-1}$ | 33.8 ± 3.6 |
| R | 1.19 ± 0.02 |
| METs | 19 ± 1 |

TABLE 1. Values (mean ± SD) of the respiratory parameters obtained during maximal effort.

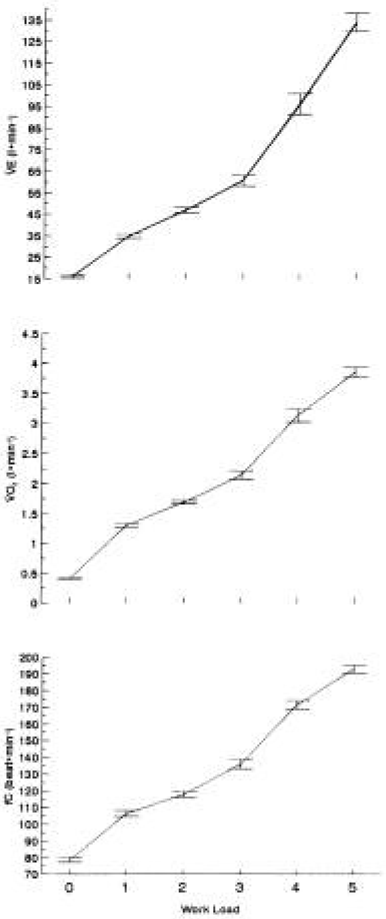


**Figure 1--·VE, ·VO2, and fC (mean ± SE) throughout the exercise test.**

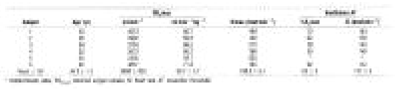

TABLE 2. Some individual data at maximal effort and at anaerobic threshold

## DISCUSSION

In relation to the anthropometric testing, it is worth pointing out that the subjects constituted a homogeneous group, with a medium stature, body build, and low body fat in accordance with the results previously reported by Sloan and Masali (33). With the exception of the higher limb circumferences and total skinfold thickness average values obtained by us, all the other anthropometric measurements were almost identical to those previously reported for the same age group in a wide sample of the male Sherpa population (33). This fact may be explained by the higher physical activity and, generally, better nutrition status of climbers in relation to farmers of the Sherpa highland community.

Subjects with higher $\cdot VO_{2max}$ at sea level had higher uptakes at the simulated high altitudes (6). Although this fact does not seem to ensure tolerance of high altitude (6,25), it is, however, absolutely necessary to meet minimal oxygen requirements in certain conditions, such as those presented in extreme altitude where levels almost incompatible with life are reached (37). Given that the $\cdot VO_{2max}$ gradually decreases with altitude-hypoxia (5,6,35), elevated levels of$\cdot VO_{2max}$ at sea level should allow a better aerobic metabolism and performance at extremely high altitudes (6,29). It is possible that a minimum sea-level $\cdot VO_{2max}$ between 49 and 61 $mL \cdot min^{-1} \cdot kg^{-1}$ is necessary to reach the summit of Mt Everest without supplementary oxygen (29).

With regard to the studies carried out to date that assess the functional capacity of Himalayan highlanders, we would like to emphasize that: 1) with the exception of the step testing (5,17), and walking uphill with load performed on Sherpas (31), or cycle-ergometer in Tibetans (34,38), the other studies were performed with nonspecific ergometric devices such as the cycle-ergometer in Sherpa natives (21,27); 2) apparently contradictory values of $\cdot VO_{2max}$ have been obtained at low altitude (17,18,31) or even at sea level (5,21), when compared with several of those obtained at high altitude (21,27,34) where lower values should be expected. Pugh et al. (27) obtained a $\cdot VO_{2max}$ of 43 $mL \cdot min^{-1} \cdot kg^{-1}$ in one Sherpa tested at 5,800 m using a cycle-ergometer; Lahiri et al.(21) reported values of 49 and 46 $mL \cdot min^{-1} \cdot kg^{-1}$ in two Sherpas at 4,880 m by means of the same ergometer; and Sun et al. (34) reported values between 50 and 58 $mL \cdot min^{-1} \cdot kg^{-1}$ in nine Tibetans tested in the same manner at 3,658 m. Likewise, high$\cdot VO_{2max}$ values have also been found in Andean Amerindians tested at high altitude: Vogel et al. (36) reported values of 53 and 57 $mL \cdot min^{-1} \cdot kg^{-1}$ in two Peruvian Indians tested by means of cyclo-ergometer at 4,350 m; Hurtado (15) informed of functional capacity equivalent to an average of [almost equal to]55 $mL \cdot min^{-1} \cdot kg^{-1}$ by using a treadmill in 12 subjects of the same Indian group tested at 4,550 m. If we take into account that altitude causes a well-documented exponential reduction of $\cdot VO_{2max}$ (6,35,37), and that this relationship is approximately the same in highlanders and lowlanders (5), the above-mentioned values obtained between 3,600 and 5,800 m should correspond to a $\cdot VO_{2max}$-increase of between[almost equal to]18 and 40% at sea level. Consequently, this fact would suggest that all the aforementioned Himalayan and Andean highlanders could have high values of oxygen uptake during maximal exercise at sea level. However, some of these isolated cases reported in the literature may be applicable to very select individuals, as has been previously stated (5).

On the other hand, in all studies carried out previously, specifically on Sherpa natives at low altitude-two subjects tested at 2,100 m (31), five subjects at 1,300 m (17), three subjects (5), and one subject (21) at sea level-$\cdot VO_{2max}$ values similar to those observed in climbers of lowland dwellers have been reported. Although there are several exceptions that have shown high $\cdot VO_{2max}$, the most frequent value in Western high-altitude climbers of similar age ranged between an average of 50 and 60 $mL \cdot min^{-1} \cdot kg^{-1}$(8,25,29). However, it is noteworthy that in three of these studies performed on Sherpas, the natives did not reach their theoretical maximum functional values of ventilation or heart-rate response (17,21,31). The higher maximal aerobic power found by us could very well be one of the physiological variables that contribute to the high performance of this select group of elite native climbers tested. This fact could be attributable, partially, to their exceptional athletic endurance (this group boasts the best climbing background of all the present Sherpa population) and also perhaps to the treadmill test never previously performed on Sherpas, who are rural highlanders not accustomed to cycling because of the nature of their local terrain. In addition to this, $\cdot VO_{2max}$ has been reported as 20% higher for treadmill testing than the cycle ergometer in mountain climbers both before and after one high-altitude expedition (8). However, the marked *genu-valgum-recurvatum* and flat foot condition presented by all the subjects tested by us, which produces a peculiar walking and running style on a smooth surface (personal observation), probably contributed to a certain efficiency limitation on the ergometer especially during the final phase of the exercise test. To support this observation, a greater mechanical efficiency of the Himalayan Sherpas and Andean Quechuas in their natural environment has been suggested (15,31). This fact could explain the high oxygen-uptake levels shown for each stage of the test (Fig. 1).

In addition to the aerobic power and cardiac chronotropic reserve shown by this select group at sea level, their high performance on the mountain could be due to: 1) the greater utilization of glucose rather than fatty acids as energetic substrate, as demonstrated by Hochachka et al.(12,13), which allows a larger production of ATP per volume of oxygen consumed; 2) the higher ventilatory efficiency particularly at high altitude (5,21,27); 3) the existence of a higher anaerobic threshold-which in our study is elevated in comparison with those individuals who do not follow regular and intensive training and show a threshold of between 40 and 60% of the $\cdot VO_{2max}$(32)-that can reach levels almost as high as the$\cdot VO_{2max}$ detected in the average results shown by the other studies performed on Sherpas previously at low altitude (5,17,21,31). This high anaerobic threshold can be of special value given that, although the Sherpa natives generally exercise at relatively low work intensity, they do so in a hypoxic environment.

As regards the implications of the metabolic threshold, it is worth pointing out that: 1) we calculated the ventilatory anaerobic threshold, which should correspond to a concentration of serum lactate of around 2 $mmol\cdot L^{-1}$ (9); 2) given the enzymatic modifications of the highlanders that attenuate the production of lactate (14), it is presumable that they could sustain, in a stable manner, levels of physical exercise substantially higher than those corresponding to the ventilatory anaerobic threshold. It is well-known that exercise intensities producing plasma lactate levels below 4 $mmol\cdot L^{-1}$ can be sustained for long periods of time (22).

The aerobic qualities, maximal oxygen uptake, and anaerobic threshold found in our study are even more striking if the following factors are taken into account: the age of the subjects, their absence of training program, and, as reported, the relatively low intensity of their routine physical activity at high altitude since childhood which reduces the speed of task-execution, compensating for the environmental hypoxic conditions (26). However, we cannot reject the possibility of the existence of a special genetic endowment in Himalayan (19,23) and Andean ethnic groups (13). This assumption is borne out by the existence of higher blood-oxygen saturation at birth and during the first months of life reported in Tibetans compared with Chinese Han descendants born at the same altitude (24). Furthermore, the $\cdot VO_{2max}$ values reported for the adult population of both ethnic groups living in Lhasa(Tibet, 3,658 m) were shown to be higher in Tibetans (34,38).

Also noteworthy are the very high maximal cardiac frequencies reached, taking into account the age of the members studied by us. It is well known that a few days of exposure to hypobaric hypoxia induces a decrease in the maximal chronotropic cardiac response to exercise, as is well documented for lowland dwellers (1,11), as well as in Sherpa natives exposed to an altitude higher than that of their habitual residence (5). This appears to be due to a reduction in the density of myocardial [beta]-adrenoceptors (2), adenosine receptors (1), and to an increased density of muscarinic receptors (16). Such cardiac chronotropic"downregulation" is rapidly reversible upon return to lower altitudes, at least, in Caucasian lowland dwellers exposed to chronic hypoxia (28). However, a long-term exposure to high altitudes tends to bring the maximal chronotropic cardiac response back to normal (1,21). The elevated maximal heart rate observed in Himalayan highlanders has been well documented by several studies (18,27,38), which have even detected maximal cardiac frequencies of 210 bpm in two 24-yr-old (mean) Tibetans tested at an altitude of 3,658 m (34), and 195 bpm in one 42-yr-old Sherpa at 4,880 m (21). Although more studies are needed to understand what really happens at the level of myocardial receptors in native highlanders transferred to sea level, our results support the idea that the corresponding maximal heart rates detected during the exercise test could be similar to those reached by them during maximal effort levels when climbing at high altitude. Nevertheless, we cannot rule out the possibility that a certain "rebound effect" could take place after the rapid withdrawal from chronic exposure to hypoxia.

In conclusion, our results appear to be in accordance with some other studies performed on highland ethnic groups tested at high altitude. However, the present work is novel in that it reports for the first time on six elite Sherpa climbers transferred to sea level who showed both high aerobic capacity and very high maximal heart rate. Although these findings have been obtained in a very select sample of the Himalayan population, determining respiratory gas exchange by means of state-of-the-art technology and applying a relatively specific stress test protocol, we believe that they may provide valuable information as to the metabolic reserve shown by some professional climbers of the Sherpa community. This report supports the idea that natural selection and long-training in a hostile environment enable some humans to reach the world's highest summits repeatedly without the use of supplementary oxygen.

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HIGHLANDERS; OXYGEN UPTAKE; HEART RATE; ANAEROBIC THRESHOLD; ALTITUDE; HYPOXIA; MOUNTAIN CLIMBING