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SHORT REPORT

Maximal aerobic power in high-altitude runners

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Summary. Maximal aerobic power ($\dot{V}O_2max$) was assessed in seven male and one female middle- and long-distance recreational runners residing in La Paz, Bolivia (3600 m). All runners were born and raised at high altitudes (>2500). Mean $\dot{V}O_2max$ in the male runners was 60·8 ml/kg/min while $\dot{V}O_2max$ in the female runner was 55·5 ml/kg/min. These values are higher than in any previously reported sample of either trained or untrained high-altitude natives. In addition, mean $\dot{V}O_2max$ in the La Paz male runners and $\dot{V}O_2max$ in the La Paz female runner were very similar to those found in comparable low-altitude samples of recreational athletes, suggesting that the cardiorespiratory systems of both normally active and highly active native Andean highlanders are capable of successfully responding to the stress of hypobaric hypoxia. This ability may have both developmental and genetic components.

1. Introduction

Maximal aerobic power ($\dot{V}O_2max$) has long been used to assess the effectiveness of cardiorespiratory responses to the stress of hypobaric hypoxia (Baker 1969). For example, lowland sojourners to high altitude exhibit substantial decreases in $\dot{V}O_2max$, indicating a failure to respond successfully to this stress (Buskirk 1976). However, mean $\dot{V}O_2max$ in young adult highland males is similar to that of lowland sedentes (Burkirk 1978), suggesting that their cardiorespiratory systems have successfully responded to the stress of hypobaric hypoxia (Baker 1969, Buskirk 1978, Frisancho, Martinez, Velasquez, Sanchez, and Montoye 1973). Expressed differently, these data suggest that the cardiorespiratory systems of normally active young adult highland males can be considered to have successfully responded to a hypobaric hypoxic environment. However, not all individuals in highland populations are young adult males with average activity patterns. A better understanding of the effects of hypobaric hypoxia therefore requires examining other groups, such as females with the additional oxygen requirements of pregnancy (Haas 1980), elderly highlanders with age-associated declines in $\dot{V}O_2max$ (Greksa and Beall 1989), or athletes, the focus of the present report. Athletes are of interest because optimal athletic performance involves operating the cardiorespiratory system at or near its maximum capacity.

2. Subjects and methods

The subjects for the present study included seven male and one female middle- and long-distance runners belonging to a running club in La Paz, Bolivia (average altitude of about 3600 m). All subjects were born and raised at high altitudes (>2500 m). The age distribution of the sample is described in table 1. The runners reported running 50–97 km per week, with a median weekly distance of 78 km. The genetic background of the sample is not known but, based on phenotype and surnames (six subjects with two Spanish surnames and two subjects with one Aymara and one Spanish surname), they are probably best described as mestizos.

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Stature and weight were measured by one researcher using standard techniques (Weiner and Lourie 1981). The exercise tests were conducted in 1983 in the exercise physiology laboratory of the Clínica Nacional del Deporte and the Instituto Boliviano de Biologia de Altura in La Paz, Bolivia (3600 m; mean $P_B = 499{\cdot}3$ mmHg, range: 498–500 mgHg). Subjects were given a continuous and progressive exercise test on a Collins P3800 treadmill. Two 30-s collections of expired air were collected in Douglas bags at peak exertion. The volumes of air in the Douglas bags were determined with a Singer dry gas meter. The fractions of O_2 and CO_2 in the expired air were determined with a Servomex model OA150 O_2 analyser and a Gould Mark III Capnograph CO_2 analyser, respectively. An electrocardiogram was recorded on a Hewlett–Packard two-channel recorder with leads in the CM5 position. Measurements made at peak exertion included heart rate (HRmax), respiratory exchange ratio (Rmax), maximal aerobic power ($\dot{V}O_2$ STPD), and pulmonary ventilation ($\dot{V}_E$max BTPS).

The criteria for maximal exertion were visual signs of fatigue and a respiratory exchange ratio of greater than 1·20. Two subjects were excluded by these criteria. Another subject met the criteria for maximum exertion but had a $\dot{V}O_2$max which fell more than 3 standard deviations below the mean for the remainder of the sample. Since his level of physical fitness was well below that of the remainder of the sample, he was also excluded from the analyses.

$\dot{V}O_2$max in the La Paz runners was compared with the following samples (see figure 1). Sample 1 consists of the La Paz runners. Sample 2 is based on five high-school male athletes (mean age 17·0 years) from Leadville, Colorado (3100 m) who were tested at high altitude (Grover, Reeves, Grover and Leathers 1967). Sample 3 is based on 42 male (mean age 25·9 years) and 44 female (mean age 21·9 years) trained university physical education students (Åstrand, Åstrand, Hallbäck and Kilbom 1973). Sample 4 includes 67 well-conditioned male (mean age 36·2 years) and nine female (mean age 32·4 years) runners (training distance 64–160 km/week) (Hagan, Strathman, Strathman and Gettman 1980). Sample 5 consists of six middle-distance male runners (mean age 17·1 years) (Dill and Adams 1971). Sample 6 includes 16 females whose $\dot{V}O_2$max values were above the average for their age (mean age 21·9 years) (Drinkwater, Horvath and Wells 1975). Sample 7 consists of nine female marathon runners (age range 19–29 years; mean training distance 88·7 km/week) (Upton, Hagan, Lease, Rosentsweig, Gettman and Duncan 1984). Finally, sample 8 is based on 20 male and 10 female members of the Swedish National Team (Saltin and Åstrand 1967). This sample includes the fittest athletes from an already select group, and therefore provides a reasonable estimate of the very upper limits of $\dot{V}O_2$max at low altitude. These samples differ in body size, making adjusting for body size by dividing $\dot{V}O_2$ (l/min) by body weight somewhat problematic (Tanner 1949). However, $\dot{V}O_2$max (ml/kg/min), even with its limitations, has proved to be the best available measure of the overall functional capacity of the cardiorespiratory system (Shephard 1985). In addition, body weight proved to be as effective as alternative methods for controlling for body size (Bailey, Ross, Mirwald and Weese 1978) in comparisons of $\dot{V}O_2$max between highland boys of differing ages and ethnicities and, as a result, body sizes (Greksa, Spielvogel and Paredes-Fernandez 1985).

3. Results and Discussion

Age, anthropometry, and maximal exercise responses of the La Paz runners are described in table 1, and figure 1 compares $\dot{V}O_2$max between the La Paz runners and selected samples of athletes. Based on perceived exertion, heart rate, and respiratory

Table 1. Age, anthropometry, and selected maximal exercise responses of La Paz runners.

	Age (years)	Stature (cm)	Weight (kg)	*HR*max (b/min)	*R*max	$\dot{V}$Emax (l BTPS)	$\dot{V}O_2$max (l STPD)	$\dot{V}O_2$max (ml/kg/min)
Female 1	17·1	161·4	53·6	193	1·26	130·0	2·97	55·46
Male 1	26·5	166·7	49·9	184	1·21	132·5	2·71	54·40
Male 2	25·8	170·2	57·9	193	1·26	151·2	3·15	54·52
Male 3	22·9	159·4	58·7	186	1·28	149·6	3·37	57·53
Male 4	35·6	178·3	64·1	176	1·28	186·3	3·99	62·28
Male 5	27·1	179·2	65·2	176	1·28	203·3	4·08	62·67
Male 6	36·0	158·6	52·7	176	1·37	159·0	3·53	67·16
Male 7	20·7	170·9	59·9	186	1·36	171·3	4·02	67·20
Male $\bar{X}$	27·8	169·0	58·3	182	1·29	164·7	3·55	60·82
(SD)	(5·9)	(8·2)	(5·6)	(7)	(0·06)	(24·1)	(0·52)	(5·45)

exchange ratio, the runners in the present study were working at maximal levels of exercise.

Mean $\dot{V}O_2$max in the male runners was 60·8 ml/kg/min, which is higher than that found in other studies of both trained (Aparicio, Antezana, Spielvogel and Carreón 1987, Coudert and Paz Zamora 1970, Grover *et al.* 1967 (Sample 2 in figure 1), Mazess 1969) and untrained (Baker 1969, Elsner, Bolstad and Forno 1964, Frisancho *et al.* 1973, Greksa, Haas, Leatherman, Thomas and Spielvogel 1984, Hochachka, Stanley, Matheson, McKenzie, Allen and Parkhouse 1991, Mazess 1969, Velasquez 1970, Vogel, Hartley and Cruz 1974) highland adult males. This finding is of course consistent with the hypothesis that this is a well-trained and highly fit sample. To our knowledge there are no published data on $\dot{V}O_2$max in highland adult females but, based on comparisons with trained lowlanders (see below), the La Paz female runner is also very fit.

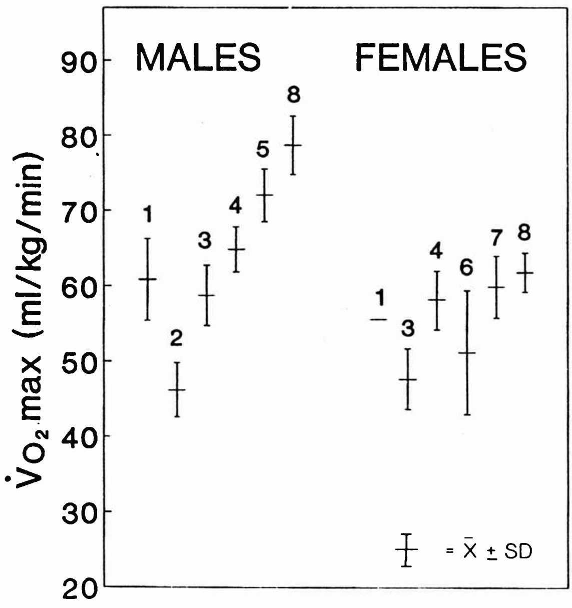

Figure 1. $\dot{V}O_2$max in selected samples of high- and low-altitude athletes. (Sample 1 = La Paz runners; Sample 2 = highland runners of European ancestry; Samples 3, 4, and 6 = low-altitude recreational runners; Samples 5, 7, and 8 = low-altitude elite runners; see text for details.)

Since they did not have access to training facilities, and since running was a leisure-time activity, the La Paz runners can best be described as recreational athletes. The lowland comparison samples include both recreational athletes (Samples 3, 4, and 6) and elite athletes (Samples 5, 7, and 8). Both groups were well-trained at the time they were tested but elite athletes tend to be a select group who benefit from both superior training facilities and a superior genetic endowment and, as a result, tend to have higher $\dot{V}O_2$max values than recreational athletes (Shephard 1985). Mean $\dot{V}O_2$max in the La Paz male runners and the $\dot{V}O_2$max of the La Paz female runner are very similar to those of the lowland recreational athletes (figure 1: Samples 3, 4, and 6). On the other hand, the La Paz athletes, as expected, have $\dot{V}O_2$max values which are lower than found in low-altitude elite athletes (figure 1; Samples 5, 7, and 8).

It is difficult, if not impossible, to ensure that the La Paz runners and the lowland recreational athletes (Sample 3, 4, and 6) have similar genetic endowments and training schedules, both of which influence $\dot{V}O_2$max (Shephard 1985). However, all of the subjects in these samples were recreational athletes and, as far as can be determined, their training schedules did not differ greatly, suggesting that they are probably reasonably comparable samples. Previous research has suggested that the cardiorespiratory systems of normally active young adult Andean males have successfully responded to the stress of hypobaric hypoxia, as judged by their having $\dot{V}O_2$max values similar to those of comparable samples of lowlanders (Baker 1969, Buskirk 1978, Frisancho *et al.* 1973). The results of the present study suggest that the same is true of highly active Andean male highlanders, and is probably also true of females, although additional studies of females are certainly needed. With respect to at least males, therefore, these data suggest that the range of cardiorespiratory function over which Andean natives can successfully respond to hypobaric hypoxia appears to be fairly large, and perhaps includes levels of functional capacity higher than generally assumed. Expressed differently, the constraints imposed by a hypobaric hypoxic environment on Andean natives appear to operate at the upper limits of the distribution of cardiorespiratory function, or at least above those of very fit highland runners.

Previous research indicates that the enhanced $\dot{V}O_2$max values of highlanders of both Andean and European ancestry are achieved during the period of growth and development, suggesting that exposure to hypobaric hypoxia during critical periods of development, or developmental adaptation, is involved (Frisancho *et al.* 1973, Greksa *et al.* 1985). However, since Andean runners have substantially higher $\dot{V}O_2$max values than highland runners of European ancestry (Grover *et al.* 1967, figure 1: Sample 2), it is possible that genetic factors may also be involved. This hypothesis is supported by the finding that high-to-low altitude migration results in about twice as large an increase in $\dot{V}O_2$max in native highlanders of European ancestry (Grover *et al.* 1967) as it does in Andean highlanders (Hochachka *et al.* 1991, Velasquez 1970, Vogel *et al.* 1974) and by the finding that Andean highlanders appear to possess energetically more efficient metabolic systems than subjects of European ancestry (Hochachka *et al.* 1991).

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Zusammenfassung. Für 7 männliche und 1 weibliche Mittel- und Langstrecken laufende Freizeitsportler(in) aus La Paz, Bolivien (3600), wurde die maximale Sauerstoffaufnahmekapazität (VO_2max) bestimmt. Alle Läufer waren in großen Höhen (>2500 m) geboren und aufgewachsen. Bei den männlichen Läufern betrug der VO_2max Wert 60·8 ml/kg/min während der entsprechende Wert sind höher als alle bisher für trainierte bzw. untrainierte Eingeborene aus großen Höhen mitgeteilten Werte. Darüber hinaus waren die VO_2max Werte der Läufer und der Läuferin aus La Paz denen sehr ähnlich, die für vergleichbare Stichproben von Freizeitsportlern aus geringen Höhen beobachtet wurden. Daraus läßt sich schließen, daß das Herzkreislaufsystem sowohl normal als auch hoch aktiver Eingeborener aus dem Andernhochland in der Lage ist, erfolgreich auf den Stress einer hypobarischen Hypoxie zu reagieren. Diese Fähigkeit kann sowohl genetische als auch entwicklungsbedingte Komponenten haben.

Résumé. La puissance aérobie maximum (VO_2max) a été établie chez 7 coureurs masculins et 1 coureur féminin de fond et de demi-fond, résidant à La Paz en Bolivie (3600 m). Tous étaient nés et avaient grandi à haute altitude (>2500 m). Le VO_2max moyen chez les coureurs masculins est 60·8 ml/kg/mn et de 55·5 ml/kg/mn chez le coureur féminin. Ces valeurs sont plus les élevées de toutes celles qui ont jamais été enregistrées chez des personnes de haute altitude, entraînées ou non. De plus les moyennes de VO_2max trouvées chez ces coureurs des deux sexes de La Paz, sont très semblables à celles rencontrées dans des échantillons comparables d'athlètes au repos en basse altitude, ce qui suggère que les montagnards andins ayant une activité normale comme ceux qui ont une activité intense, sont capables de répondre efficacement au stress d'hypoxie hypobarique. Cette capacité peut résulter de composants à la fois développementaux et génétiques.