Pulmonary gas exchange and acid-base state at 5,260 m in high-altitude Bolivians and acclimatized lowlanders

PETER D. WAGNER,1 MAURICIO ARAOZ,2 ROBERT BOUSHEL,3 JOSÉ A. L. CALBET,3 BIRGITTE JESSEN,3 GÖRAN RÅDEGRAN,3 HILDE SPIELVOGEL,2 HANS SØNDEGAARD,3 HARRIETH WAGNER,1 AND BENGT SALTIN3

1Department of Medicine, University of California, San Diego, La Jolla, California 92093
2Instituto Boliviano de Biología de Altura, Bolivia; and 3Division of Physiology, Department of Medicine, University of California, San Diego, La Jolla, California 92093

Received 30 January 2001; accepted in final form 9 November 2001

THE REMARKABLE ABILITIES of high-altitude natives to perform work at altitude are well known (15), and much research has been carried out to understand the physiological basis of this phenomenon. Considerable attention has been focused on the lungs, and several studies point to differences in lung structure and function between high-altitude natives and lowlanders of Tibet (23), South America (15), and even the United States (6). Some of the differences appear to be inherited adaptations consequent to generations of living at altitude. Others may result from individual lifelong or at least long-term high-altitude residence, whereas others may occur over the short term of days to weeks. Principal observations are that lung volumes are greater than predicted by sea-level tables (15, 23) and that diffusing capacity is also elevated (4–6, 9, 15). Reduced ventilatory response to hypoxia is often (6, 15) but not always (22) seen, resulting in arterial Pco2 values that are higher in high-altitude natives than in lowlanders. Despite this, arterial oxygenation is defended during exercise by a smaller alveolar-arterial Po2 difference (A-a)Po2 in natives compared with lowlanders, such that arterial Po2 saturation is similar but not always (22) seen, resulting in arterial Pco2 values that are higher in high-altitude natives than in lowlanders. Despite this, arterial oxygenation is defended during exercise by a smaller alveolar-arterial Po2 difference (A-a)Po2 in natives compared with lowlanders, such that arterial Po2 saturation is similar between groups (6) or even higher in natives (23). These findings have mostly been obtained at or below 4,000 m.

During a recent expedition to Mt. Chacaltaya (altitude 5,260 m) near La Paz, Bolivia, we took the opportunity to further explore differences in pulmonary function between South American high-altitude natives and lowlanders. This expedition was focused primarily on circulatory and skeletal muscle changes with acclimatization, and this required arterial blood sampling at rest and during exercise. Thus, whereas pulmonary function was not a primary target of the expedition, the gas-exchange and acid-base differences seen in the lowlanders compared with natives were substantial, prompting their description in the present report. What this study offered beyond those described above is

Address for reprint requests and other correspondence: P. D. Wagner, Div. of Physiology, Univ. of California, San Diego, 9500 Gilman Dr., MC 0623A, La Jolla, CA 92093 (E-mail: pdwagner@ucsd.edu).

http://www.jap.org 8750-7587/02 $5.00 Copyright © 2002 the American Physiological Society 1393
was a side-by-side comparison of lowlanders and Andean natives using identical methods and with direct arterial blood sampling not available in Schoene et al.’s work (15) in subjects of similar population ancestry. An unusual additional aspect of the present study was that the lowlanders had acclimatized for 9 wk at the chosen altitude before measurements. Most acclimatization studies have not allowed such a long period at a single altitude but have followed subjects as they inexorably continued to ascend, preventing attainment of steady-state conditions at any point. Moreover, the studies of Dempsey et al. (6), Zhuang et al. (23), and Schoene et al. (15) were all carried out at substantially lower altitudes (3,100, 3,658, and 3,900 m, respectively) than the present effort, which took place at 5,260 m. In the present study, measurements were made both at rest and during exercise and addressed the following questions: 1) Does 9 wk at this constant high altitude permit complete pH normalization (i.e., restoration of arterial pH to near 7.40) in lowlanders? 2) Does acute hypoxia in natives (who were necessarily transported on the day of the study from La Paz, altitude 3,600–4,100 m, to 5,260 m) produce a substantial additional stimulus to breathing at rest or during exercise, and is measurable in exercise capacity as would occur for lowlanders moving between these altitudes? 3) Is arterial oxygenation during exercise still defended in natives at 5,260 m as appears to be the case at lower altitudes, and, if so, are the physiological mechanisms similar to those described above in prior studies [higher diffusing capacity and lower (A-a)PO2]? 4) Is arterial acid-base regulation similar in natives and acclimatized lowlanders?

METHODS

Subjects. This study used nine lowlanders from Denmark and seven Bolivian natives of mixed European and Amerindian population ancestry, lifetime residents of La Paz at between 3,600 and 4,100 m. All provided informed consent to protocols approved by both Danish and Bolivian ethical committees (Copenhagen-Fredericksberg Ethical Review Committee and Comité de Etica del Colegio Médico de La Paz). Anthropometric and key additional physiological attributes are given in Table 1. All 16 subjects were healthy, habitually active, and nonsmokers. The Danes were physically active college students with an interest in outdoor recreation, whereas the Bolivians indulged in a variety of regular social activities including soccer. Only one Bolivian was a trained athlete (marathon runner). There were small differences in age (Bolivians 3 yr older, P = 0.05) and height (Bolivians 12 cm shorter, P = 0.01), but weight and body mass index were not significantly different. Both hemoglobin concentration and hemoglobin Po2 at 50% saturation of hemoglobin (P50) were similar in the two groups (Table 1) as well. Note from Table 1 that maximal cycling power output (that is, highest power sustainable for the 5 min required for stabilization and data collection) and associated O2 uptake (V02) when breathing ambient air at 5,260 m were also similar between groups.

The lowlanders spent 9 wk at 5,260 m, and the studies were done in the last week. The lowlanders all undertook two brief (2–3 day) climbs of neighboring 6,000 m peaks (one in week 2 and one in week 7) and a 1-day recreational bicycle descent to 2,000 m in week 6. Otherwise, they all remained at Mt. Chacaltaya at 5,260 m for the entire period. None displayed evidence of high-altitude pulmonary or cerebral edema at any time.

Table 1. Anthropometric and exercise capacity characteristics of high-altitude natives and lowlanders after acclimatization

<table>
<thead>
<tr>
<th></th>
<th>High-Altitude Natives</th>
<th>Lowlanders</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>7</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Age, yr</td>
<td>27.6 ± 1.6</td>
<td>24.3 ± 0.5</td>
<td>0.05</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>62.6 ± 2.2</td>
<td>67.0 ± 3.4</td>
<td>NS</td>
</tr>
<tr>
<td>Height, cm</td>
<td>164 ± 2</td>
<td>176 ± 3</td>
<td>0.01</td>
</tr>
<tr>
<td>Maximal cycling, W</td>
<td>217 ± 5</td>
<td>229 ± 13</td>
<td>NS</td>
</tr>
<tr>
<td>(ambient air at 5,260 m)</td>
<td>2.47 ± 0.09</td>
<td>2.43 ± 0.16</td>
<td></td>
</tr>
<tr>
<td>Maximal cycling, W</td>
<td>229 ± 8</td>
<td>282 ± 15</td>
<td>0.01</td>
</tr>
<tr>
<td>(55% O2 at 5,260 m)</td>
<td>NS compared with air</td>
<td>P &lt; 0.001 compared with air</td>
<td></td>
</tr>
<tr>
<td>[Hb], g/dl (maximal exercise)</td>
<td>20.0 ± 0.4</td>
<td>19.2 ± 0.7</td>
<td>NS</td>
</tr>
<tr>
<td>Hb-P50, Torr at 37°C, pH = 7.40 and Pco2 = 40 Torr</td>
<td>28.4 ± 0.2</td>
<td>30.5 ± 0.7</td>
<td>NS</td>
</tr>
</tbody>
</table>

Values are means ± SE; n, no. of subjects. V02, O2 uptake; [Hb], hemoglobin concentration; P50, Po2 at 50% saturation of hemoglobin.
a 10-min rest, subjects again cycled at 120 W for 2 min, after which work rate was rapidly raised to the previously determined individual peak rate known to be sustainable for 5 min. During the final 2 min of this 5-min period, duplicate measurements were again obtained. With subjects still pedaling, a higher work rate was imposed if subjects indicated ability to continue, and measurements were repeated within 2 min. When each subject could increment work rate no further, the inspired gas was switched from ambient air [barometric pressure = 408 Torr; inspiratory Po2 (PiO2) = 75 Torr] to ∼55% O2 (PiO2 = 195–200 Torr) while the subject continued to pedal. After 2 min, another set of measurements was taken, and work rate was further incremented individually if tolerated to attain a new peak power output. A final set of measurements was then obtained under these conditions.

It should be noted that the above was actually a subset of the entire day’s protocol. Those elements that pertained to questions other than lung-related issues are not described here. These include submaximal and maximal exercise runs using a single-leg knee extensor effort and also cycle exercise after parasympathetic nervous system blockade (reported elsewhere, Ref. 3). The knee extensor runs were done before those described for the present study and were separated from the present cycle exercise by an hour of rest, but the parasympathetic blockade experiments were always done after the present study had been completed.

Measurements. Other than VO2, VCO2, and ventilation, the principal data were obtained from arterial blood samples and consisted of Po2, PCO2, and pH (Radiometer ABL5); saturation and hemoglobin concentration (Radiometer OSM3); and plasma lactate levels (ABL5). All values of Po2, PCO2, and pH were corrected to blood temperature measured by the femoral venous catheter thermistor. Cardiac output was measured in lowlanders by indocyanine green dye dilution with injection in a peripheral (antecubital) vein and femoral arterial sampling (3). In natives, a noninvasive method for measuring cardiac output was chosen to minimize catheter placements and blood loss. We used the acetylene uptake method (2) and employed the SensorMedics VO2max system (SensorMedics, Yorba Linda, CA) to measure acetylene (and an insoluble reference gas, methane) concentrations at the mouth. This system also measures ventilation and O2 and CO2 concentrations and so provided all of the input data required for calculation of cardiac output as explained in Barker et al.’s paper (2). Without any equipment to measure acetylene solubility, we assumed for all subjects an average blood:gas partition coefficient of 0.8 on the basis of Barkers’ results and an estimate from Jibelian et al. (10) of the contribution of the higher than sea-level hemoglobin concentration.

Calculations. Oxygen-diffusing capacity of the lungs (DlO2) was not directly measured at rest or during exercise. However, a value for DlO2 could be calculated from the measured blood-gas data by use of a numerical forward-integration algorithm (19) as follows. First, by using the measured pulmonary Vo2, cardiac output, and arterial O2 concentrations, mixed venous O2 levels were computed for each subject. Similar calculations were performed for CO2. Alveolar Po2 was also determined for each subject by using the alveolar gas equation and taking alveolar PCO2 to be equal to arterial PCO2. Between these venous and alveolar values for Po2 and PCO2, a value of DlO2 was found (by using the numerical integration procedure in an iterative manner) that predicted the measured arterial Po2 and PCO2 for each subject. The key assumption, made for both subject groups, was that all of the (A-a)Po2 found during exercise at 5,260 m was due to diffusion limitation and none was caused by ventilation-perfusion inequality. The diffusing capacity was therefore calculated by assuming a homogeneous lung and, as a result, is a conservative lowest estimate. This assumption is seen in DISCUSSION.

Analysis of data. The principal objective of this study was to compare several elements of exercise performance between high-altitude natives and acclimatized lowlanders. This was done by two-way ANOVA (subjects × exercise levels, the latter by repeated measures) followed by unpaired t-tests comparing subject groups at any exercise level when ANOVA indicated significant group effects. Data in figures and tables are given as means ± SE because the major interest is in mean differences between the two subject groups.

RESULTS

Resting gas exchange. Lowlanders hyperventilated compared with natives. Figure 1 shows resting arterial Po2, arterial PCO2, and (A-a)Po2 in both groups. Po2 was 8 Torr higher (50.0 ± 1.1 vs. 42.1 ± 0.7, P < 0.001) and PCO2 9 Torr lower (21.1 ± 0.9 vs. 30.0 ± 0.3, P < 0.001) in lowlanders. However, in both groups, (A-a)Po2 was similar and not different from zero.

Arterial pH was significantly higher in the lowlanders at 7.48 ± 0.007 vs. 7.43 ± 0.004 in the natives, P < 0.001, whereas bicarbonate levels were lower (15.1 ± 0.5 meq/l in lowlanders; 19.4 ± 0.3 meq/l in natives, P < 0.001). As a result, calculated base excess was more negative in the lowlanders (−5.6 vs. −3.5 meq/l respectively, P < 0.001). Resting arterial blood lactate levels were similar (1.5 and 1.4 mmol/l, P not significant). The lowlanders showed greater perturbation of acid-base balance than the natives. It is remarkable that in the natives, despite rapid ascent from 3,600–4,100 to 5,260 m over 2 h and an arterial O2 saturation of 77%, arterial pH was 7.43, hardly different from a normal pH of 7.40 or from values of resting arterial pH of 7.41 reported previously in such natives at 3,600 m (17).

Fig. 1. Resting arterial Po2 (PaO2) and PCO2 (PaCO2) and alveolararterial Po2 difference [(A-a)Po2] at 5,260 m in subjects breathing ambient air. Lowlanders hyperventilate compared with high-altitude natives, but (A-a)Po2 is essentially zero in both groups. Values are means ± SE.
These differences in ventilation at $V_{O_2}$max occurred in the face of identical arterial $P_{O_2}$ (45.6 (lowlanders) and 46.0 Torr (natives)) and $O_2$ saturation (72.1 (lowlanders) and 72.3% (natives)), an arterial pH that was higher in the lowlanders (7.37 vs. 7.33, $P = 0.04$), and an arterial blood lactate concentration that was lower in the lowlanders (8.7 vs. 11.5 mmol/l, $P = 0.04$).

Comparing arterial $P_{CO_2}$ values during peak exercise in air and (at the same power output) in 55% $O_2$ provides additional insight into the ventilatory responsiveness to hypoxia. Recall that, during air breathing, both maximal cycling power output and arterial $P_{O_2}$ were similar in the two groups. In the natives, arterial $P_{CO_2}$ rose 6.4% from $26.7 \pm 1.0$ to $28.4 \pm 0.8$ Torr, $P = 0.02$. In the lowlanders, $P_{CO_2}$ rose 22.8% from $19.3 \pm 0.8$ to $23.7 \pm 0.8$ Torr, $P < 0.001$. The relative increase in $P_{CO_2}$ (and therefore fall in alveolar ventilation) was thus 3.6-fold greater in lowlanders than in natives when hypoxia was eliminated.

Arterial oxygenation and diffusing capacity during exercise. With note taken of a similar cardiac output response to exercise (Fig. 3A), important to diffusion equilibration, arterial $P_{O_2}$ during exercise was not different between groups (Fig. 3B). This contrasts with the higher $P_{O_2}$ in lowlanders at rest and occurred despite the substantial differences in ventilation shown in Fig. 2. Arterial $O_2$ saturation followed arterial $P_{O_2}$ (Fig. 3C), resulting in similar values for arterial $O_2$ concentration (not shown).

With the lower arterial $P_{CO_2}$ yet similar $P_{O_2}$ during exercise, (A-a)$P_{O_2}$ was higher in the lowlanders (Fig. 3D). Although the absolute differences are not large, they occurred on the steep region of the $O_2$-hemoglobin dissociation curve and thus are important for $O_2$ transport.

$O_2$ diffusing capacity calculated during maximal exercise was 40% lower in the lowlanders [119 ± 6 ml/(min·Torr)] than in the natives [167 ± 15 ml/(min·Torr)], $P = 0.01$.

Acid-base balance at rest and during exercise. During maximal exercise, arterial pH fell from resting levels by similar amounts in the two groups (7.48 to 7.37 in the lowlanders, a difference of 0.11; 7.43 to 7.33 in the natives, a difference of 0.10). Although arterial $P_{CO_2}$ values also fell by similar amounts (2 and 3 Torr, respectively), there was a significant difference in the arterial blood lactate concentrations: 8.7 ± 0.8 mmol/l in lowlanders and 11.5 ± 1.0 mmol/l in natives, $P = 0.04$. Despite the lower blood lactate levels, calculated base deficit was not smaller in the lowlanders. In fact, base deficit was 12.0 ± 0.5 meq/l compared with 10.7 ± 0.7 in the natives. Figure 4 brings out these differences in the relationship between base deficit and lactate levels for the two groups. The scatter about the regression lines comes mostly from differences between subjects in each group, given that individual regressions all had correlation coefficients of ≥0.8. A comparison of the slopes and intercepts of the base deficit-lactate relationship revealed that both the slope and intercept were higher in the lowlanders ($P < 0.001$ each). In particular, the slope was 20% higher in the lowlanders.

**Ventilatory response to exercise.** Figure 2A shows that $O_2$ consumption at rest, submaximal exercise, and maximal exercise while breathing ambient air at 5,260 m was essentially identical in the two groups, allowing a comparison that is not encumbered by questions of relative vs. absolute work rates nor by differences in efficiency of $O_2$ utilization. Figure 2B shows that lowlanders continued to mount a greater ventilatory response than natives throughout exercise. At maximal $V_{O_2}$ ($V_{O_2}$max), minute ventilation was 163 l/min in the lowlanders vs. 131 l/min in the natives, a difference of 24%, $P = 0.05$. Not surprisingly, arterial $P_{CO_2}$ remained lower in the lowlanders throughout exercise as shown in Fig. 2C. At $V_{O_2}$max, arterial $P_{CO_2}$ was 7.4 Torr lower in the lowlanders (19.3 vs. 26.7, $P < 0.001$). Arterial $P_{CO_2}$ fell slightly from rest to exercise in both groups (by 2 Torr in lowlanders and 3 Torr in natives, $P$ not significant).
(0.97 ± 0.02 meq/mmol compared with 0.81 ± 0.03 in the natives), implying less ability to buffer lactic acid during exercise, despite the similarity in hemoglobin concentrations (Table 1).

DISCUSSION

The discussion corresponds to the four questions laid out in the introduction.

Rate of acclimatization in lowlanders at altitude.

This study shows that, even after 9 wk at an altitude of 5,260 m, resting arterial pH is still alkaline (7.48), despite considerable renal bicarbonate excretion. These results contrast with those of Dempsey et al. (6), in which resting arterial pH was 7.42 for both sojourners and natives despite the latter having acclimatized for less time (4–45 days). However, this was at 3,100 m, substantially lower than in Bolivia. That arterial pH eventually normalizes at 5,260 m is suggested by the present native data. Their pH was 7.43 despite having ascended from La Paz (3,600–4,000 m, P\textsubscript{O}\textsubscript{2} of 95 Torr) to Chacaltaya (5,260 m, P\textsubscript{O}\textsubscript{2} of 75 Torr) in just 2 h and thus having been acutely exposed to significantly greater hypoxia than at their altitude of residence. The data of Vincent et al. (17) further support this conclusion: Arterial pH at La Paz was 7.41 and P\textsubscript{CO}\textsubscript{2} was 31.3 Torr in natives breathing air at rest, barely different from our data at 5,260 m.

Zhuang et al. (23) showed that, at 3,658 m, high-altitude natives in Tibet also have a resting arterial pH of 7.40 and P\textsubscript{CO}\textsubscript{2} of 30 Torr. They additionally assessed lowlanders who had been at 3,658 m for 1–2 yr and found pH to be 7.45, with arterial P\textsubscript{CO}\textsubscript{2} at 28 Torr. Why were the lowlanders in both the present study and that of Zhuang hyperventilating to maintain pH at 7.45–7.48 after 9 wk to 2 yr at altitude? Acute hyperventilation associated with catheterization or the mouthpiece is a possibility but seems unlikely. Our lowlanders were young Danish students used to mouthpieces, catheters, and research studies, whereas for the natives this was a completely new experience, especially catheter placement, blood sampling, breathing on a mouthpiece, and being subjected to additional acute hypoxia. If anything, acute hyperventilation would have been expected in the natives, the opposite of what was observed. Moreover, Zhuang et al. (22)
found that arterial saturation was unaffected by presence of a mouthpiece. A second possibility is that the classical Rahn and Otis (13) line depicting alveolar PO\textsubscript{2} and PCO\textsubscript{2} in acclimatized subjects does not represent complete acclimatization, which produces even greater ventilation with more time at altitude. Plotting the lowlander data on the Rahn and Otis diagram (Fig. 5) indicates that our subjects had an alveolar PO\textsubscript{2} ~5 Torr higher and PCO\textsubscript{2} 4 Torr lower than expected.

This suggests a response in which the time to reach a pH of 7.40 increases with increasing altitude. In Operation Everest II, mean resting arterial pH was 7.44, 7.46, 7.50, 7.53, and 7.56 at altitudes equivalent to 0, 4,750, 6,100, 7,620, and 8,848 m, respectively (16). Data from Grassi et al. (8) and Samaja et al. (14) show greater ventilation over the 9 wk was happening at a rate sufficient to prevent renal function from keeping pace.

**Possible influence on natives of rapid ascent from La Paz to Chacaltaya.** Because our equipment could not be duplicated in La Paz nor readily moved between Chacaltaya and La Paz, the natives were studied at Chacaltaya (5,260 m) on arrival after a 2-h drive from La Paz (3,600–4,100 m). We therefore anticipated acute hyperventilation because Pi\textsubscript{O\textsubscript{2}} was 20 Torr lower than in La Paz. However, despite a resting arterial PO\textsubscript{2} of 42 Torr (saturation 77%), PCO\textsubscript{2} was 30 Torr and pH 7.43. Vincent et al.’s (17) La Paz data in similar resting subjects showed that arterial PO\textsubscript{2} was 56 Torr (saturation estimated at about 90%), PCO\textsubscript{2} was 31.3 Torr, and pH was 7.41. Thus, despite the large drop in saturation, there was evidence of very little increase in ventilation.

Vincent et al.’s (17) subjects fall right on the Rahn and Otis (13) line for acclimatized subjects (at 3,600 m) shown in Fig. 5 of the present paper. Rahn and Otis further showed how acute hypoxia affects alveolar PO\textsubscript{2} and PCO\textsubscript{2} in lowland subjects already acclimatized to various altitudes. From Fig. 5 of their paper, one estimates that La Paz natives taken acutely to 5,260 m would have had an alveolar PO\textsubscript{2} of 45–46 Torr and PCO\textsubscript{2} of 27–28 Torr, whereas our subjects displayed values of 42 and 30 Torr, respectively.

Furthermore, because arterial saturation during constant-load exercise in each group was raised from 73 to 99% by breathing 55% O\textsubscript{2}, the natives increased arterial PCO\textsubscript{2} by only 6.4% (whereas lowlanders increased PCO\textsubscript{2} by 22.8%). These findings are compatible with the work of Schoene et al. (15), who showed that hypoxic ventilatory drive in high-altitude natives was blunted. The native responses are all the more astonishing given the low O\textsubscript{2} saturation during exercise (Fig. 3) and the usual carotid body sensitivity to such hypoxemia (20).

It was feared that the acute ascent not only would represent a major ventilatory stimulus, but would also compromise exercise capacity. The outcome, however, suggests otherwise. Thus maximal cycling power output was not significantly affected: 234 ± 6 W several days earlier in La Paz, compared with 217 ± 5 W at Chacaltaya. The lack of significant decrease in exercise capacity with acute ascent from 3,600–4,100 m to 5,260 m is consistent with (but more dramatic than) the findings of Favier et al. (7), who in similar subjects found only a minor (8%) decrease in VO\textsubscript{2}\textsubscript{max} at La Paz (3,600 m) between 31.4% O\textsubscript{2}, equivalent to sea-level air, and ambient air. This insensitivity of VO\textsubscript{2}\textsubscript{max} to Pi\textsubscript{O\textsubscript{2}} suggests that muscle metabolic capacity in natives has been downregulated over time in response to reduced O\textsubscript{2} availability.

**Pulmonary gas exchange during exercise.** This study extends to 5,260 m the work of both Dempsey (6) at 3,100 m in North American high-altitude natives and Zhuang (23) at 3,658 m in Tibetan high-altitude natives. As in their work, a lower (A-a)PO\textsubscript{2} preserves arterial PO\textsubscript{2} and saturation at values seen in acclimatized lowlanders at the same work rate, despite the natives’ higher arterial PCO\textsubscript{2}.

Because theoretical and experimental work shows that at altitude most of the (A-a)PO\textsubscript{2} is due to alveolar-capillary diffusion limitation (18, 21), the likely basis of the lower (A-a)PO\textsubscript{2} in high-altitude natives is higher diffusing capacity associated with larger lungs, as previously suggested (15, 23). Piiper and Scheid (11, 12) have shown that the degree of diffusion limitation depends on the ratio DL\textsubscript{O\textsubscript{2}}/β·QT, where DL\textsubscript{O\textsubscript{2}} is the O\textsubscript{2} diffusing capacity of the lungs, β is the slope of the O\textsubscript{2} dissociation curve, and QT is cardiac output. In the present study, β and QT (Fig. 3) were similar between natives and lowlanders. The β depends on hemoglobin concentration (similar, Table 1), in vivo P\textsubscript{50} (similar at 31.7 and 32.0 Torr), and arterial and venous PO\textsubscript{2} and saturation (arterial similar, Fig. 3; venous similar by calculation from VO\textsubscript{2}, cardiac output, and arterial val-

Fig. 5. Mean resting blood-gas data in lowlanders and natives plotted on a figure based on the Rahn and Otis (13) diagram. Vincent et al.’s (17) data on Bolivian natives resident at La Paz are also shown. Our native data suggest no ventilatory response to rapid ascent to 5,260 m. Our lowlander response shows substantial departure from the data of Rahn and Otis, with lower PCO\textsubscript{2} and higher PO\textsubscript{2} indicating greater ventilation.

J Appl Physiol • VOL 92 • APRIL 2002 • www.jap.org
ues, Figs. 2 and 3). Thus it is the 40% higher calculated DlO\textsubscript{2} in natives that underlies the smaller (A-a)PO\textsubscript{2} and preserves arterial PO\textsubscript{2}.

Cardiac output was measured by dye dilution in lowlanders and by acetylene uptake in natives. The acetylene method has been validated (2), and the cardiac output-VO\textsubscript{2} relationship was similar in the two groups (Fig. 3A), suggesting agreement. However, there may have been systematic differences between the two methods. We therefore calculated the effect of potential errors in cardiac output on estimated DlO\textsubscript{2} and found that a 10% error produces a 3.4% error in the same direction in estimated DlO\textsubscript{2}. Thus to explain the 40% higher DlO\textsubscript{2} in the natives on errors in cardiac output would require that peak cardiac output had been overestimated by 220% and was not 20 but only 9 l/min. This is impossible because even complete muscle O\textsubscript{2} extraction would not have provided the measured VO\textsubscript{2}. If cardiac output in the lowlanders had been lower because of blood withdrawal during its measurement, this could have reduced estimated DlO\textsubscript{2}. However, each measurement requires only 20 ml blood and moreover this was reinjected immediately. This cannot therefore explain the lower lowlander DlO\textsubscript{2}.

A specific assumption made in the calculation of DlO\textsubscript{2} is that ventilation-perfusion (V\textsubscript{A}/Q) inequality plays an insignificant role in the (A-a)PO\textsubscript{2} of exercise at this altitude. Because neither group had an (A-a)PO\textsubscript{2} at rest (Fig. 1), resting V\textsubscript{A}/Q inequality must have been minimal. Because effects of V\textsubscript{A}/Q inequality on (A-a)PO\textsubscript{2} lessen with increasing hypoxia, whereas those of diffusion limitation increase (11, 12, 21), the postulate that V\textsubscript{A}/Q inequality during exercise contributed little to the (A-a)PO\textsubscript{2} is also reasonable. Work from Operation Everest II (18), using the multiple inert gas elimination technique to distinguish diffusion limitation from V\textsubscript{A}/Q mismatching, confirmed that diffusion limitation was the major contributor to the (A-a)PO\textsubscript{2}.

Relating exercise DlO\textsubscript{2} [119 ml/(min·Torr), lowlanders and 167 ml/(min·Torr), natives] to maximal normoxic exercise capacity (282 W, lowlanders and 229 W, natives; Table 1) provides an astonishing result: The ratio of pulmonary diffusing capacity to maximal normoxic power output is 0.73 ml/(min·Torr·W) in the natives and only 0.42 ml/(min·Torr·W) in the lowlanders. The natives therefore have 173% of the diffusing capacity of the lowlanders per watt of normoxic exercise capacity. It should be recalled that there were no differences in hemoglobin concentration to explain this (Table 1). This very large difference presumably stems from structural differences in their lungs. Whereas in the lowlanders (at sea level) spirometry revealed vital capacity (111% predicted) and resting carbon monoxide diffusing capacity (92% predicted) that were within normal limits, vital capacity (134% predicted Caucasian sea-level values, P < 0.01) and diffusing capacity (142% predicted, P < 0.001) were elevated in the natives when referenced to North American norms. The high DlO\textsubscript{2} values in natives during exercise appear directionally compatible with these data and the literature (6, 15).

\textbf{Acid-base balance during exercise.} Despite similar blood Hb concentration, there appear to be acid-base control differences between the lowlanders and natives. As shown in Fig. 4, calculated base deficit rose linearly with lactate concentration in both groups, but with different slopes. The mean slope in the lowlanders (0.97 ± 0.02 meq/l per mmol/l lactate) is similar to values at sea level [for example, 1.03 in Operation Everest II (16) and 1.13 in the same Danish lowlanders studied later in Copenhagen] and is a reasonable (1:1) stoichiometric outcome. On the other hand, the slope in natives averaged only 0.81 ± 0.03, a highly significant (P < 0.001) difference implying greater lactate-buffering capacity. The explanation for these unexpected differences cannot be stated with certainty but may just reflect the Henderson-Hasselbalch equation: On the Davenport diagram, flattening of PCO\textsubscript{2} isopleths occurs as PCO\textsubscript{2} falls. Thus, at a lower PCO\textsubscript{2}, the change in pH (x-axis) for a given change in base deficit (y-axis) at constant PCO\textsubscript{2} would be greater. The higher arterial PCO\textsubscript{2} values in the natives (Fig. 2) are consistent with this idea. It is also possible that the natives may have had a larger blood volume, because lowlanders are known to reduce plasma volume at altitude. If this were the case, it could also have contributed to the better buffering of lactate in the natives.

Whatever the mechanism, the consequences for exercise limitation may be considerable. Recall that, at V\textsubscript{O}\textsubscript{2 max} in ambient air, lactate levels were higher in the natives (11.5 mmol/l) than in the lowlanders (8.7 mmol/l). Had lowlander lactate levels been as high, arterial pH (at the same PCO\textsubscript{2}) would have been 7.25 instead of 7.37 as measured. Combined with the severe hypoxemia (73% saturation) and the evidence that ventilatory stimulation was already great (PCO\textsubscript{2} 19 Torr, pH 7.37), it is likely that intolerable dyspnea would have occurred. We therefore suggest that the relatively lower buffering capacity of the lowlanders contributed to their exercise limitation.

In conclusion, this study, performed at 5,260 m, comparing Bolivian high-altitude natives resident at La Paz (3,600–4,100 m) to sea-level natives acclimated for 9 wk at 5,260 m, has demonstrated a number of pulmonary and other physiological differences between them. 1) Even 9 wk of residence at 5,260 m fails to accomplish complete normalization of arterial pH in lowlanders, and ventilation is greater than expected from prior data. This raises the question of whether full acclimatization at this altitude requires much longer than previously suspected, possibly lifelong or even more than one generation of exposure. 2) Reduced ventilatory response to hypoxia in high-altitude natives, both at rest and during exercise, still occurs as in previous reports at lower altitudes, despite severe acute arterial desaturation caused by rapid ascent from La Paz. 3) (A-a)PO\textsubscript{2} values during exercise are smaller in natives likely because of increased diffusing capacity associated with larger lungs. This enables, at lower ventilatory cost, the same arterial saturation as
in lowlanders. When related to metabolic potential assessed by maximal exercise capacity in normoxia, pulmonary diffusing capacity is 73\% greater per watt in natives than in lowlanders. 4) Lactate buffering appears enhanced in natives, defending arterial pH in the face of both higher lactate and PCO₂ levels than in acclimatized lowlanders.

We thank Professor Carlos Aguirre from the Academia Nacional de Ciencias de Bolivia and Dr. Pedro Miranda, Director of the Laboratorio de Comisión Fisica at Chacaltaya, where the experiments were conducted, for invaluable help. The use of the facilities at the Club Andino Boliviano was most valuable and appreciated. We also were conducted, for invaluable help. The use of the facilities at the

REFERENCES