Maximal performance at altitude and on return from altitude in conditioned runners


Laboratory for Human Performance Research Institute for Science and Engineering, The Pennsylvania State University, University Park, Pennsylvania

BUSKIRK, E. R., J. KOLLIAS, R. F. AKERS, E. K. PROKOP, AND E. P. REATEGUI. Maximal performance at altitude and on return from altitude in conditioned runners. J. Appl. Physiol. 23 (2) : 259-266. 1967. - Maximal aerobic capacity as measured by the maximal oxygen intake ($V_{O_{2 \text{max}}}$), ventilation ($V_{E \text{max}}$), heart rate ($HR_{\text{max}}$), bicycle-riding time, and outdoor running times, were measured in six well-conditioned runners at altitudes of 300 m, 4,000 m, and after return to 300 m. The runners maintained a training regimen at all altitudes. $V_{O_{2 \text{max}}}$ decreased 26% at 4,000 m as compared to the values at 300 m. $V_{E \text{max}}$ was increased at 4,000 m, and $HR_{\text{max}}$ remained relatively unchanged. $V_{O_{2 \text{max}}}$ was no higher following return to 300 m than it had been before going to altitude. A synergistic effect of exercise plus hypoxia as a training stimulus was not found. Performance times were similar on return from altitude in track events to what they were before going to altitude. Pulmonary edema did not occur in any of the runners. After 4-5 weeks at altitude, the runners could compete on equal terms in soccer with native residents at 4,000 m.

work performance; work capacity; aerobic capacity; maximal oxygen intake; hypoxia; maximal ventilation; exercise heart rate

Several investigations dealing with the effects of altitude-induced hypoxia on work capacity have been conducted on men who varied widely in age, degree of physical fitness and conditioning, and length of stay at altitude (1, 2, 6, 7, 10-12, 14, 16). Because of the heterogeneity of the test subjects used in these investigations and because the men were frequently "better conditioned" at the termination of their sojourn at altitude, the precise effects of hypoxia on work capacity remain perhaps ill defined. Increased work capacity and improved track performance upon return from altitude have been attributed to high-altitude training (2, 3), although the rationale for these changes remains obscure and contradictory evidence exists (12). Because of the variability in reported results, the questions arose as to the impact of moderate hypoxia on a) physical work capacity, b) rate of adaptation to altitude as indicated by work capacity, and c) subsequent sea-level performance of well-conditioned young men who maintained a constant state of conditioning while living at altitude. We attempted to answer these questions by studying well-conditioned and highly trained young college runners at 300 m, 4,000 m, and on return to 300 m. The Pennsylvania State University field laboratory in the highlands of Peru (4,000 m in the village of Nuñoa) was used for the altitude phase of the study. For the most part, only relatively simple procedures were undertaken that could logically be conducted in a field laboratory.

SUBJECTS, METHODS, AND PROCEDURES

Physical characteristics of six members of the Pennsylvania State University varsity track team who participated as subjects in this study appear in Table 1. All runners, with the exception of DG who was a sprinter, participated in cross-country running in the fall of 1964 and were middle-distance or distance runners during the spring track season of 1965. Laboratory testing began in May 1965 during the latter part of the track season. Thus, all runners were in excellent physical condition at the beginning of the study and their training continued at a high level thereafter, although their conditioning tempo was reduced at altitude.

Maximal work capacity tests were conducted with the Monark bicycle ergometer (Ab Cykelfabriken Monark, Varberg, Sweden) and the Fleisch-Jaquet ergometer (Instrumentation Associates, New York). The use of the Fleisch-Jaquet ergometer was interposed because of the necessity to leave the lightweight Monark ergometer at the Peruvian laboratory. The resistance of the Monark is measured in kilopond meters per minute (kpm/min) while the Fleisch-Jaquet is measured in watts, therefore,
TABLE 1. Personal characteristics of runners, including running event they performed most proficiently

<table>
<thead>
<tr>
<th>Subj</th>
<th>Age, yr</th>
<th>Ht, cm</th>
<th>Wt, kg*</th>
<th>Best Event†</th>
</tr>
</thead>
<tbody>
<tr>
<td>JB</td>
<td>19</td>
<td>182</td>
<td>71.0</td>
<td>880 yd</td>
</tr>
<tr>
<td>DG</td>
<td>21</td>
<td>178</td>
<td>77.0</td>
<td>440 yd</td>
</tr>
<tr>
<td>RL</td>
<td>21</td>
<td>182</td>
<td>75.6</td>
<td>1 and 2 mi</td>
</tr>
<tr>
<td>AM</td>
<td>19</td>
<td>184</td>
<td>74.9</td>
<td>1 and 2 mi</td>
</tr>
<tr>
<td>GM</td>
<td>21</td>
<td>176</td>
<td>66.3</td>
<td>880 yd</td>
</tr>
<tr>
<td>RR</td>
<td>21</td>
<td>171</td>
<td>64.1</td>
<td>2 mi</td>
</tr>
</tbody>
</table>

* Body weights reported are the weights measured at Pennsylvania State University before going to altitude. Body weight did not change significantly thereafter.
† All runners with the exception of DG ran cross country during the fall.

A factor of 6.0 was used to convert watts to kilopond meters per minute to approximate similar work loads. The progressive test of work capacity was designed to exhaust a man within a 10-min period. With the Monark ergometer, the subject rode at 3.0 kp at 60 rpm (1,080 kpm/min) for the first 2 min, and the work load was increased 0.5 kp/min thereafter until the subject reached exhaustion. With the Fleisch-Jaquet ergometer, work began by pedaling at 60 rpm at a work load of 176.5 w (1,080 kpm/min) for 2 min, and the work load was increased 30 w/min. Extra loading weights had to be made for the 30-w increments. The total revolutions and bicycle-riding time were recorded for each subject.

All subjects breathed through a low-resistance Collins triple-J valve during the last 2–3 min of their ergometer ride. As the subject approached his maximal work capacity, serial 1-min samples of expired gas were collected in Douglas bags. Expired gas was analyzed with a paramagnetic oxygen analyzer (Beckman model E2) and an infrared carbon dioxide analyzer (Mines Safety Appliances, Lira model 300). Thus, discrete measurements of oxygen consumption (\(\dot{V}_O_2\)), carbon dioxide production (\(\dot{V}_CO_2\)) (both STPD), respiratory exchange ratio (R), and ventilation (\(V_E\), BTPS and STPD) were obtained. \(V_E\) was measured by evacuating the timed Douglas-bag collections through a Parkinson-Cowan dry gas meter. Heart rate was measured with either bipolar ECG telemetry or stethoscope auscultation over the apex of the heart. Oxygen pulse (\(\dot{V}_O_2\)/pulse) and ventilation equivalent (\(V_E/\dot{V}_O_2\)) were also calculated.

The ergometric testing procedure, gas collection, and methods of analysis were comparable at each altitude. Maximal oxygen intake (\(\dot{V}_O_2_{max}\)) was taken as the highest oxygen intake obtained during the terminal portions of the ride. \(\dot{V}_O_2_{max}\) usually occurred in the next to the last minute because pedaling frequency was usually voluntarily reduced during the last minute as exhaustion developed. The subject simply could not keep up.

An attempt was made to secure running times in duplicate on a track at each altitude. The local topography of the Peruvian highlands where the runners resided was favorable for the construction of a temporary track for carrying out daily workouts and time trials.

Figure 1 shows a schematic diagram of the travel schedule and period of residence at the Pennsylvania State field laboratory at Nuñoa, Peru. After 48 days residence at 4,000 m, JB, RL, and AM returned to the United States for additional testing in Colorado at Mt. Evans, 4,375 m (7 days) and Alamosa, 2,300 m (7 days) before returning to Pennsylvania State University. The data collected at Mt. Evans and Alamosa are not presented here with the exception of the running times that appear in Table 3. Subjects DG, GM, and RR continued residence at 4,000 m for 63 days and then returned directly to Pennsylvania State University. The number of days in transit both to and from altitude is shown in Fig. 1. Weather data for the two laboratory sites are shown in Table 2.

The prealtitude measurements were made the week before leaving Pennsylvania State University. The day at altitude on which each measurement was made is indicated in the tables and figures. During the post-altitude period, subjects JB, RL, and AM were studied on the 2nd and 15th day after their return from altitude, and subjects DG, GM, and RR on the 7th and 15th day.

Rigorous statistical treatment of the data was inadvisable because of the restricted degrees of freedom.

![Fig. 1. Schematic diagram of travel schedule.](image-url)
TABLE 2. Daytime range in environmental conditions at test sites

<table>
<thead>
<tr>
<th>Location</th>
<th>Months and Season</th>
<th>Temp, °F</th>
<th>Relative Humidity, %</th>
<th>Alt, m</th>
<th>Barometric Pressure, mm Hg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pennsylvania State</td>
<td>May, June (summer)</td>
<td>56-88</td>
<td>95-98</td>
<td>300</td>
<td>725-742</td>
</tr>
<tr>
<td>Peru</td>
<td>June, July, August (winter)</td>
<td>35-62</td>
<td>95-98</td>
<td>4,000</td>
<td>470-476</td>
</tr>
<tr>
<td>Pennsylvania State</td>
<td>September (summer-fall)</td>
<td>64-91</td>
<td>96-97</td>
<td>300</td>
<td>726-742</td>
</tr>
</tbody>
</table>

Indoor laboratory environments were maintained between 65-76 °F at both test sites.

with n = 6. The logistics of the field work in Peru precluded use of more subjects. If a change in a particular variable was in the same direction in all six subjects, this was regarded as significant on a nonparametric basis.

RESULTS

\( \dot{V}_{O_{2max}} \). Individual values, averages, and a broad schematic trend line are presented in Fig. 2. These data were obtained during maximal exercise tests at 300, 4,000, and on return to 300 m. All runners exhibited a marked reduction of \( \dot{V}_{O_{2max}} \) at 4,000 m. On the average \( \dot{V}_{O_{2max}} \) was reduced 29% on days 3 and 21 and 26% on day 48 at altitude. Thus, most subjects showed a slight increase in \( \dot{V}_{O_{2max}} \) with extended altitude residence; however, the increment was small (average 200 ml) and amounted to only 3%. Despite a body weight loss of 1-2 kg at altitude, the percent decrease in \( \dot{V}_{O_{2max}} \) in both liters/min and ml/min per kg were similar. At 300 m, average \( \dot{V}_{O_{2max}} \) was 63 ml/min per kg and after 48 days at 4,000 m, \( \dot{V}_{O_{2max}} \) averaged 49 ml/min per kg or a 23% decrease. On return from altitude \( \dot{V}_{O_{2max}} \)'s of all runners were similar to prealtitude values.

Ventilation. VE (BTPS) during the terminal portion of maximal exercise increased markedly after arrival at altitude (125% on day 3) and continued to increase slightly throughout the stay at altitude (132% on day 48) (Fig. 2). VE (STPD) was considerably less immediately after arrival (74%), but a slow rise with continued altitude residence occurred in most of the runners, and on day 48, average VE (STPD) was 81% of the pre-altitude value. Postaltitude VE (BTPS) and VE (STPD) were elevated on the average, 117% and 113%, respectively.

Respiratory exchange ratio (R). During the first 9 days of residence at altitude, R for each runner during the terminal portion of exhausting exercise was substantially elevated above prealtitude values (Fig. 3). With acclimatization, R values gradually declined and ap-

### TABLE 3. Comparative running times at various altitudes

<table>
<thead>
<tr>
<th>Subj</th>
<th>Event</th>
<th>Best Collegiate Time</th>
<th>PSU Prealtitude, 100%</th>
<th>Days at 4,000 m</th>
<th>Days at 2,300 m</th>
<th>PSU Postaltitude</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>40-47</td>
<td>47-57</td>
<td>4 or 6</td>
<td>3 or 7</td>
<td>10 or 15</td>
</tr>
<tr>
<td>DG</td>
<td>440 yd</td>
<td>47.8</td>
<td>50.8</td>
<td>57.0 (88%)</td>
<td>54.5 (93%)</td>
<td>a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.8</td>
<td>25.9</td>
<td>24.5 (76%)</td>
<td>23.1 (82%)</td>
<td>4.0 (100%)</td>
</tr>
<tr>
<td>JB</td>
<td>880 yd</td>
<td>15.8</td>
<td>20.4</td>
<td>216.0 (97%)</td>
<td>215.0 (99%)</td>
<td>2.0 (100%)</td>
</tr>
<tr>
<td>CM</td>
<td>880 yd</td>
<td>15.8</td>
<td>20.4</td>
<td>216.0 (97%)</td>
<td>215.0 (99%)</td>
<td>2.0 (100%)</td>
</tr>
<tr>
<td>XC</td>
<td>5 mi</td>
<td>27.43.0</td>
<td>32.000 (86%)</td>
<td>4:26.0 (93%)</td>
<td>4:25.0 (92%)</td>
<td>2:32.4 (92%)</td>
</tr>
<tr>
<td>RL</td>
<td>1 mi</td>
<td>4:09.0</td>
<td>4:21.2</td>
<td>6:06.0 (78%)</td>
<td>6:09.0 (78%)</td>
<td>4:30.5 (92%)</td>
</tr>
<tr>
<td>AM</td>
<td>1 mi</td>
<td>4:32.0</td>
<td>4:45.0</td>
<td>6:06.0 (78%)</td>
<td>6:09.0 (78%)</td>
<td>4:30.5 (92%)</td>
</tr>
<tr>
<td>RR</td>
<td>2 mi</td>
<td>9:30.0</td>
<td>10:14.0</td>
<td>11:58.0 (86%)</td>
<td>11:50.0 (84%)</td>
<td>10:16.0 (100%)</td>
</tr>
<tr>
<td></td>
<td>5 mi</td>
<td>27.93.0</td>
<td>32.000 (85%)</td>
<td>10:16.0 (100%)</td>
<td>10:16.0 (100%)</td>
<td></td>
</tr>
</tbody>
</table>

XC means cross-country run on grass or dirt. Days 3 and 10 to runners who also ran in Colorado. Days 7 and 15 to runners who returned directly from Peru. a Pulled muscle. b Indicates best cross-country running time over 5-mile course. c The two boys paced themselves at 4,000 m and ran together; does not reflect competition performance. d Unofficial track record at Adams State College, Alamoso, Colo. e Cut foot while running outdoors, did not run second time trial.
FIG. 2. Maximal oxygen intake ($\dot{V}O_2\text{max}$) and ventilation ($V_{E,max}$) during maximum exercise at 300 and 4,000 m.

Approximated prealtitude levels. Postaltitude R values were essentially unchanged from those recorded during the prealtitude tests.

**Ventilation equivalent.** A small rise in the average ventilation equivalent ($\dot{V}E/\dot{V}O_2$) occurred with continued altitude residence which was due to the progressive rise in $\dot{V}E$ (STPD) while $\dot{V}O_2\text{max}$ remained relatively unchanged (Fig. 3). On return from altitude, ventilation equivalent was slightly elevated above prealtitude values due to a greater $\dot{V}E$ (STPD).

**Heart rate.** With the exception of the sprinter DG, who exhibited a consistently lower heart rate throughout his stay at altitude, maximal heart rates were more variable but, on the average, were relatively unchanged at 4,000 m (Fig. 4). On return to 300 m, heart rate averaged 180 which is approximately the same as the prealtitude average of 176. Nevertheless, in five of the six runners, their postaltitude exercise heart rate was higher than their last recorded heart rate at altitude.

$\dot{V}O_2$/pulse. Maximal oxygen pulse ($\dot{V}O_2$/pulse), the amount of oxygen utilized per heart beat, was reduced 32% on the average immediately after arrival at 4,000 m when compared to the control value obtained at Pennsylvania State University (Fig. 4). Pulse rate was slightly higher at this time and this elevation accounts for the marked decrease in $\dot{V}O_2$/pulse. Since $\dot{V}O_2\text{max}$ was essentially unchanged during the stay at altitude, the changes observed in $\dot{V}O_2$/pulse are primarily due to changes in heart rate. This is especially evident on day 48 when the average heart rate was 162 and $\dot{V}O_2$/pulse was decreased only 19% with reference to control values. On return to 300 m the average $\dot{V}O_2$/pulse was similar to the prealtitude average value.

**Bicycle-riding time.** The results obtained with the
Monark ergometer show that on day 3 at 4,000 m, average bicycle-riding time was reduced 12% compared to riding times at 300 m; however, after the 20th day, riding times at altitude approached prealtitude values (Fig. 5). Riding times were variable in some subjects at altitude and consistent in others. The variation observed in riding time was probably a reflection of the braking system in the Monark bicycle. Uneven wear on the fabric belt produced oscillations in the brake weight that varied the load, whereas pre- and postaltitude riding times on the Fleisch-Jaquet ergometer were almost identical. We attributed this difference to the smoother braking system on the Fleisch-Jaquet ergometer.

Performance times. The comparative running times for the athletes are presented in Table 3. The temporary track constructed in Peru was not ideal, but was adequate for level running. All athletes took longer to run a given distance at altitude. At altitude average running times for the 440-yard, 880-yard, 1- and 2-mile distances were 91, 82, 77, and 81% of sea-level times. Thus, the percent decrement in 1-mile performance at altitude corresponded to the percent decrease in riding time on the bicycle ergometer.

It was interesting to find that a form reversal occurred at altitude. Subject RR could never beat AM in any event at sea level; however, at altitude RR had a better running time than AM in the 2-mile run.

Three runners, JB, RL, and AM resided at 4,000 m in Peru for 50 days and returned to the United States where they spent 7 days at Mt. Evans (4,375 m) followed by 7 days at Alamosa (2,900 m), Colorado. Although RL’s mile time at 2,300 m was 15 sec slower than at 300 m, he set a new unofficial track record for the 2-mile event. At 2,300 m, subject AM’s mile time was 1 sec slower than at 300 m; however, 2-mile time was 49 sec slower. In the 880-yard event JB’s time at 2,300 m was 11 sec slower than at 300 m. Postaltitude performance times of all runners, with the exception of an injured or sick runner, were 96–100% of their prealtitude times. On no occasion during postaltitude testing did any runner better his prealtitude time.

Training at altitude. Individual daily workout schedules were recorded and gave a rough but meaningful assessment of training. Training activities consisted of interval work at increased distances, repetition runs at distances up to 1 mile, calisthenics, and recreational sports such as soccer. Immediately after arrival at altitude, the duration and intensity of training was reduced about 60%. Training continued at this level for about 3 weeks. During the 3rd and 4th weeks at altitude, the runners were capable of increasing the duration and intensity of their daily workouts about 10% to a level of 50% of their pre-altitude capabilities. A transient improvement in training occurred thereafter until the runners achieved a maximum of about 75% of their prealtitude training program. The athletes supplemented their daily track workouts by participating in other sports such as soccer, football, volleyball, and mountain climbing. Four runners, DG, RL, GM, and AM were regular players on the local soccer team which eventually won the regional championship. The highland soccer league was made up exclusively of local altitude-acclimatized players of both Spanish and Indian origins.

DISCUSSION

The decrement in aerobic capacity at altitude as measured by the maximal oxygen intake seems to follow
a fairly linear trend. It has been estimated that there is a reduction of approximately 3-3.5% for every 1,000 ft ascended above 5,000 ft \((5)\). The data reported here indicate an average reduction in \(\text{VO}_{2\text{max}}\) at 4,000 m of 26% which fits the regression line nicely. Much of the data in the literature are, however, widely scattered about the average trend. This wide variation is undoubtedly due to an increase in \(\text{VO}_{2\text{max}}\) in untrained subjects who exercised regularly at altitude, but who had not done so previously, the wide age span of the subjects used in certain studies, and the influence of acute altitude sickness in the short term studies. The training effect in \(\text{VO}_{2\text{max}}\) was minimized in our studies. The differences in experimental design and subject personnel also persist in the acute chamber exposures that have been reported. For example, Dill et al. \((9)\) found a 14% reduction in aerobic capacity at 3,800 m while Stenberg et al. \((17)\) reported a 28% decrease. The latter value would fall close to the regression line mentioned above.

No major improvement in aerobic capacity was found with continuation of training at altitude. This observation is in agreement with the work of others \((5, 8)\) but fails to confirm the view that a pronounced increase in aerobic capacity is found if training is carried out under hypoxic conditions \((2, 3)\).

Indirect considerations would indicate that the reduction in \(\text{VO}_{2\text{max}}\) at altitude is brought about largely by the reduction in \(\text{PaO}_2\). Maximal heart rate is relatively unchanged at altitude and the reduction in the maximal oxygen pulse probably reflects the decrease in \(\text{PaO}_2\) and therefore \(\text{VO}_{2\text{max}}\). It is assumed that \(\text{PvO}_2\) in muscle is minimal during hard work at 4,000 m. The above view would be supported by direct blood gas observation on dogs \((15)\).

It has also been reported that performance upon return from altitude is enhanced as a result of training at altitude \((3)\). The reasoning is that ventilatory drive is maintained at a high level, more red blood cells are available for transporting oxygen, the vasculature in skeletal muscle is better developed, and acid-base balance...
is favorable for accommodating a lactacidemia. Despite this generalized rationalization, we found no change in either the maximal oxygen intake or performance on the track pre- as compared to postaltitude. Support for the view of "no effect" has been provided, however, by the work of Grover and Reeves (12). For the moment we are content with the possibility that the runners were relatively detrained as a result of the reduction in their training intensity at altitude.

One of the problems of concern to us was the possibility of facilitating the development of pulmonary edema at altitude by attempting to achieve “all-out” performances on the bicycle ergometer and the track. Overt signs of pulmonary edema did not develop in any of the athletes although they each performed all-out on many occasions. Subjective discomfort and altitude sickness was minimal although the distinction between the gastrointestinal disturbances associated with substandard hygiene in the field situation and the effects of hypoxia were not readily apparent.

High levels of pulmonary ventilation were found at 4,000 m and ventilation remained relatively high following return from altitude. The maximal ventilations during exercise were still below their maximal breathing capacities. Their breathing during exercise, while labored, appeared to be well within their voluntary capacities.

The high ventilation rates at altitude and the low atmospheric vapor pressure produced a “burning sensation” that could be felt by the runners deep within their chests. Undoubtedly, this sensation was associated with excessive drying of the airways, perhaps as far as the bronchioles. Although daily fluid intake was not measured, 10 gal (approximately 40 liters) of drinking water was boiled each day and containers were located for easy access to the water. This volume of water was sufficient to satisfy the athletes’ thirst, but very little water remained at the end of the day. Since the urinary specific gravities for the athletes were slightly lower at altitude than at sea level, our program of water preparation and availability was apparently satisfactory. D2O-turnover studies indicated that the rate of water turnover was approximately the same in the warm 300 m environment where profuse sweating occurred during exercise, and in the cool dry 4,000 m environment where high ventilation at low humidities added to body water loss (4, 5).

The high ventilation rates at altitude served to elevate Pao2 slightly above the value obtained at rest. The average Pao2 gradient between ambient air and arterial blood was 28 mm Hg at rest and 24 mm Hg during maximal exercise. This slight elevation in Pao2 was useful for providing additional oxygen to working muscle (5).

We acknowledge the assistance of Dr. Tulio Velasques of the Instituto de Biología, Andina, Facultad de Medicina Universidad Nacional Mayor de San Marcos, Lima, Peru, for his assistance with travel, shipping, and other arrangements during our stay in Peru. We also acknowledge the collaboration and assistance of Paul T. Baker and his staff from Pennsylvania State Department of Anthropology for the work involved in initiating construction of the facilities at the Pennsylvania State University high-altitude laboratory at Núñoa, Peru, and their participation in the collection of data.

REFERENCES


