[redacted]

Final Scientific Report

National Aerounatics and Space Administration

Grant NSG 408

December 31, 1966

Part VII. The Influence of Altitude on the Anaerobic and Aerobic Capacities of Men in Work

by

L. G. Myhre, S. Robinson, J. L. Newton, C. Dawson*, E. D. Michael*
and K. Klausen

Department of Anatomy and Physiology

Indiana University

Bloomington, Indiana

and

*Institute of Environmental Stress

University of California

Santa Barbara, California

The influence of altitude on the anaerobic and aerobic capacities of men in work. Myhre, L. G. and S. Robinson. NASA NSG 408, December 31, 1967.

Abstract

Maximal aerobic and anaerobic capacities were measured on four men working to exhaustion on a bicycle ergometer before, and on an ergometer and a treadmill during a 5-week sojourn on White Mountain (altitude of 3800 m). Two series of postaltitude experiments were performed at Bloomington (264 m); the first being an exact repetition at Bloomington of each subject's last performance at altitude while in the second series the subjects continued on to complete exhaustion. In the first 10 days at 3800 m maximal values for work capacity, O_2 uptake, ventilation (STPD) and heart rate were markedly lower, but little change was observed in oxygen debt and blood lactate following work as compared with the values at Bloomington. During the remaining 5 weeks at 3800 m the tolerance time for a fixed rate of exhausting work increased 16% without a corresponding increase in maximal O_2 consumption. Accompanying this increase in work capacity were increases in lactate (30%) and O_2 debt (5%) during the stay at altitude. The increase in maximal work performance during the stay at 3800 m is attributed to an increasing ability to utilize energy from the anaerobic mechanisms and an improvement in the efficiency of work on the ergometer in the men who were not accustomed to work on the bicycle. Upon return to Bloomington maximal values for O_2 debt, O_2 uptake, ventilation (STPD), duration of work and lactate were not only greater than the altitude values, but also considerably higher than the prealtitude controls. Work that was exhausting at altitude proved to be relatively easy at 264 m; this was shown by higher but still submaximal O_2 uptake with corresponding decreases in lactate and O_2 debt. The improvements observed in the men's aerobic and anaerobic capacities during this experimental program were probably the results of the training and altitude acclimatization.

[redacted]

Many studies have been carried out during the past few years to determine the effects of high altitude upon the aerobic capacities of men for work (1-5, 7, 9-10). The purpose of the present investigation was to study both the anaerobic and the aerobic work capacities of men before, during and following a 5-week sojourn at high altitude.

PROCEDURE

This study was carried out at Bloomington, Indiana (264 m, P 743 mm Hg) and Barcroft Laboratory, White Mountain Research Station, California (3800 m, P 488 mm Hg). The physical characteristics of the subjects are given in Table 1. Subject SR is a former distance runner, nonsmoker and in good physical condition. LM is a graduate student in physical education, nonsmoker, maintaining an irregular physical fitness program. JN smokes about 20 cigarettes a day and does not ordinarily participate in strenuous physical activity. RG is a middle distance runner, nonsmoker, in good physical condition which he kept up by a regular training program even during the stay at Barcroft. During the stay at 3800 m all subjects expept RG were much more active than usual. Each man went through two exhausting work experiments and usually several submaximal work experiments every week on a bicycle ergometer or a treadmill. Except for SR, who completed two maximal work performances in as many days during the first week at altitude, a schedule was planned to provide at least two days of light work between the experiments requiring maximal effort. In addition to the exercise experiments, much of the leisure time while at Barcrodt was spent in outdoor activities such as hiking and mountain climbing. The stay at altitude was briefly interrupted about every 10 days by driving to the valley below (1220 m, P_B 666 mm Hg), for a few hours.

A von Döbeln bicycle ergometer was used in one series of O_2 debt experiments. Control experiments to determine maximal work capacity and oxygen debt were carried out on the ergometer in Bloomington about 3 weeks before ascent to

3800 m. Two series of exhausting oxygen debt experiments on the bicycle were carried out at Barcroft; one 3 to 10 days after arrival and the other near the end of the 5-week period.

Upon return to Bloomington from the mountain (3800 m) the men performed exact repetitions of their last experiments at altitude. Since they were not exhausted in the time required to exhaust them at altitude it was decided to carry out another round of experiments on the bicycle in which the subject continued on to complete exhaustion. This was delayed beyohd 2 weeks after they had returned to Bloomington. In each bicycle experiment the subject pedalled the ergometer without a load at a rate of 50 rpm for 15 minutes before the exhausting work and his steady state of O_2 requirement for this activity was determined. At 15 minutes the brakeload was quickly set at the level which was previously found at Bloomington to exhaust him in about 5 minutes. The subject continued to work on the bicycle until he reached complete exhaustion in all except the first test made after returning to Bloomington in which he stopped work at the same time at which he reached exhaustion in the final test at Barcroft. At the end of work in each experiment the brake was released to zero resistance and the subject continued to pedal at the same rate without a load during a 35-minute recovery period. Measurements of respiratory exchange were terminated at this time because the bicycle seat became uncomfortable and the subjects could not continue pedaling in a relaxed steady state.

The use of a treadmill to determine work capacity at high altitude has been, for the most part, neglected due to the physical problem of transporting such a large piece of equipment to nearly inaccessible places. Upon arrival at Barcroft, however, we were surprised to find that a small human treadmill would be available to us for the length of our stay. We took advantage of this opportunity to add exercise on the treadmill to our experimental program. This was deemed desirable, particularly since our subjects were more accustomed to running on the treadmill than riding on the ergometer.

The first O_2 debt experiments on the treadmill were carried out on three subjects during the last half of the stay at 3800 m. Within two weeks after descending to 264 m control experiments were carried out on two of the men working at the same rate and for the same length of time on the treadmill as in the experiments on the mountain (RG was unable to take part in this experiment in Bloomington). This work was not exhausting for SR and LM at Bloomington and it was decided to perform another round of treadmill experiments on all 3 men in which the work rate was increased and the men continued to exhaustion. O_2 debts and blood lactates were determined with the men reclining during recovery following each of the treadmill runs.

All oxygen debt experiments were performed in the morning with the subjects in the post-absorptive state. The subjects breathed outside air through a high-velocity low resistance respiratory valve in all experiments. Expired air was collected in a 600-liter Tissot gasometer during the run and in Douglas bags during the first few minutes of recovery while the gasometer was being emptied in preparation for collections in recovery. The detailed procedure for determining respiratory exchange and oxygen debt in the runs and recoveries is described in Part II of this report (9). All expired air samples for analysis were drawn into 50-ml syringes lubricated with ethylene glycol and analyses were made on the Haldane apparatus. Lactate was determined by the enzyme method (11) on blood samples drawn from an arm vein at approximately 5 minutes of recovery.

RESULTS AND DISCUSSION

During the first 48 hours at 3800 m all subjects, except JN, experienced headache and found it difficult to sleep at night. All men except one, (RG) showed a slight decrease in weight during the first two weeks at altitude, but had regained the loss toward the end of the 5-week period. The men's weights presented in Table 1 are from the control experiments after descent from 3800 m and are almost identical with the weights at the end of the stay

Table 1. Characteristics of subjects

Subject	Age, years	Height, cm	Weight, kg
SR	61	175.4	64.1
LM	28	188.0	74.4
JN	30	182.0	106.8
RG	20	181.7	71.4

[redacted]

Bicycle ergometer experiments. In the first experiments at 3800 m the average maximal values for oxygen consumption ($\dot{V}O_2$), blood lactate and heart rate (HR) in the exhausting bicycle experiments were reduced 19, 14 and 13% respectively while the oxygen debt (O_2 debt) was unchanged from the control values previously determined at Bloomington (Table 2 and Figs. 1 and 2). Associated with these changes was a 31% reduction in the time the men could continue working before exhaustion. Numerous workers have previously observed a reduction in $\dot{V}_{O_2}$ max at high altitude (1-5, 10, 12, and part VIII of this report). Reports in the literature differ regarding the maximal values of blood lactate and heart rate in exhausting work. Edwards (6) found as we have a reduction in man's ability to increase blood lactate in exhausting work at altitude while Buskirk et al. (3) found essentially no difference in lactates of 6 untrained runners following exhausting work on the ergometer at altitudes of 4265 and 295 m. The effect of high altitude on maximal heart rate is still a controversial question. Numerous investigators (5, 7, 9, 10) have reported a reduction in HR max during the first days, weeks, or even months at high altitude. On the contrary, Balke et al. (2) and Buskirk et al. (3) reporting on work performed at 2800 and 4265 m respectively found no significant depression in HR max. Our data confirm the former studies in that we found HR max to be depressed an average of 13% three to ten days after arrival at 3800 m.

During the 5-weeks stay at altitude the average work capacity or work time increased by 16%; this was accompanied by no significant increment in aerobic ($\dot{V}_{O_2}$ max) and only a slight increase in anaerobic (O_2 debt) energy available for the work. This indicates that an improvement in the efficiency or economy with which the men could work on the bicycle contributed to the improvement in work capacity. An improvement in efficiency in turn suggests a training effect in the men resulting from their frequent work on the bicycle during the stay at altitude. Buskirk et al. (3) reported that although no increases were observed in $\dot{V}_{O_2}$ max, O_2 debt or lactate, not only did their

[redacted]

Table 3. Responses of 3 men in oxygen debt experiments performed on a treadmill at Barcroft Laboratory, White Mountain (3800 m) and at Bloomington (264 m)

Subject	Work			V_E max, l/min		V_{O_2} max l/min	O_2 debt, liters	Lactate mg%
	mph	% grade	min	STPD	BTPS			
	16-34 days at 3800 m							
SR	4	9.0	5	68.2	[illegible]	1.33	5.43	87.0
LM	4	14.0	6	52.1	[illegible]	2.56	6.87	62.0
RG	5	11.5	4	86.1	168.8	3.16	5.32	55.6
Average			5	68.8	134.8	2.52	5.87	68.2
	7-13 days after return to 264 m*							
SR	4	9.0	5	55.8	69.5	1.91	2.50	20.6
LM	4	14.0	6	42.9	53.4	2.37	3.90	22.4
RG								
Average	4		5.5	49.4	61.5	2.15	3.20	21.5
	9-14 days after return to 264 m							
SR	5	9.0	5	84.0	104.6	2.50	7.21	84.8
LM	7	5.0	4	90.2	112.3	3.29	9.77	110.1
RG	12	2.5	4	115.5	143.8	4.40	9.45	91.2
Average			4.3	96.6	120.2	3.40	8.81	95.4

* This experiment was a repetition of each subjects' performance at altitude (Unable to repeat RG's altitude performance); all other work bouts were continued to exhaustion.

Figure 1. Average maximal values of ventilation ($\dot{V}_E$), oxygen uptake ($\dot{V}_{O_2}$) and oxygen debt of four men in exhausting work on a bicycle ergometer at Bloomington (264 m) and during 35 days at White Mountain (3800 m). The points connected with broken lines represent repetitions at Bloomington of each subject's best performance at White Mountain which was exhausting at altitude but not exhausting after descent to Bloomington.

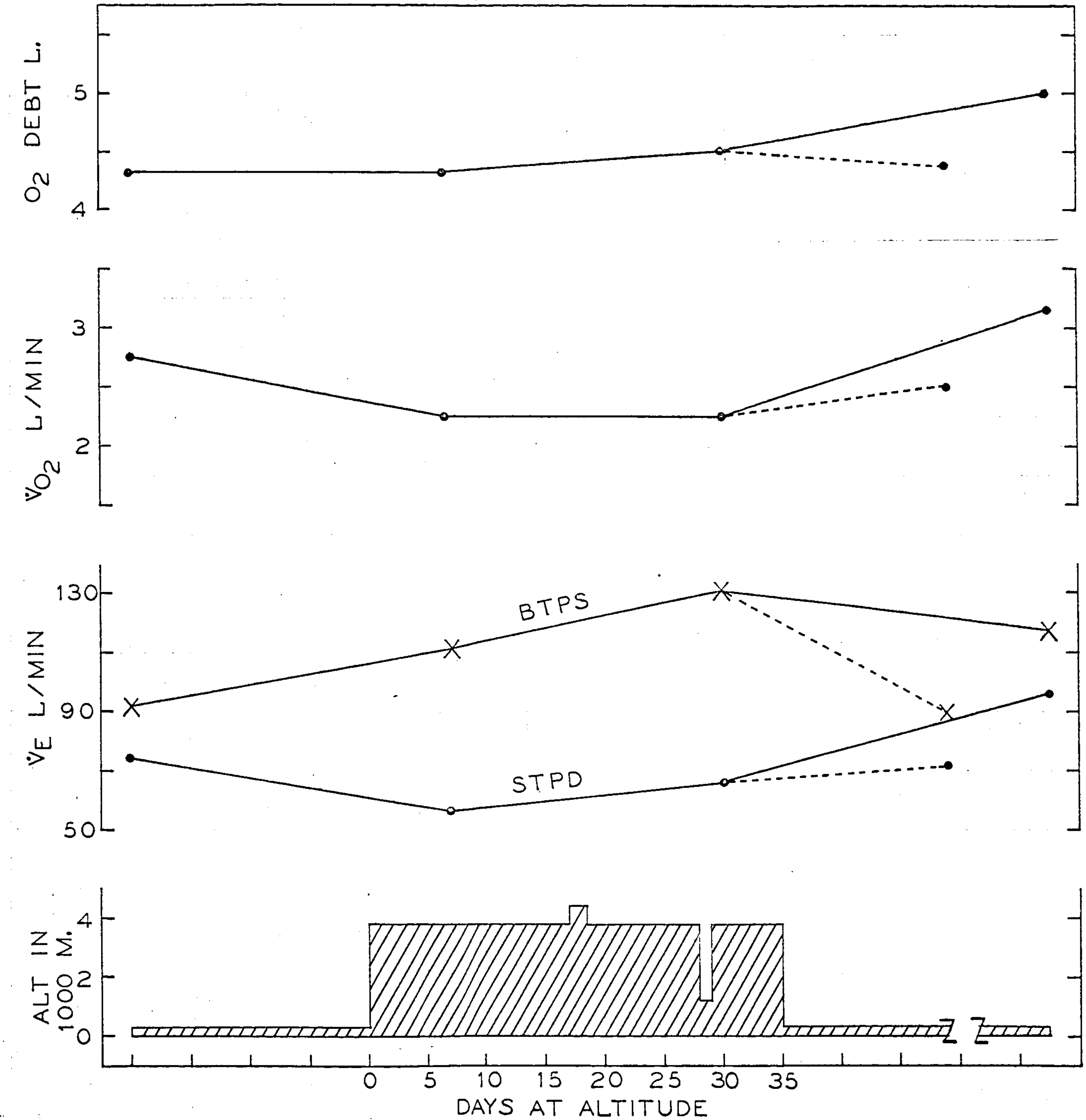
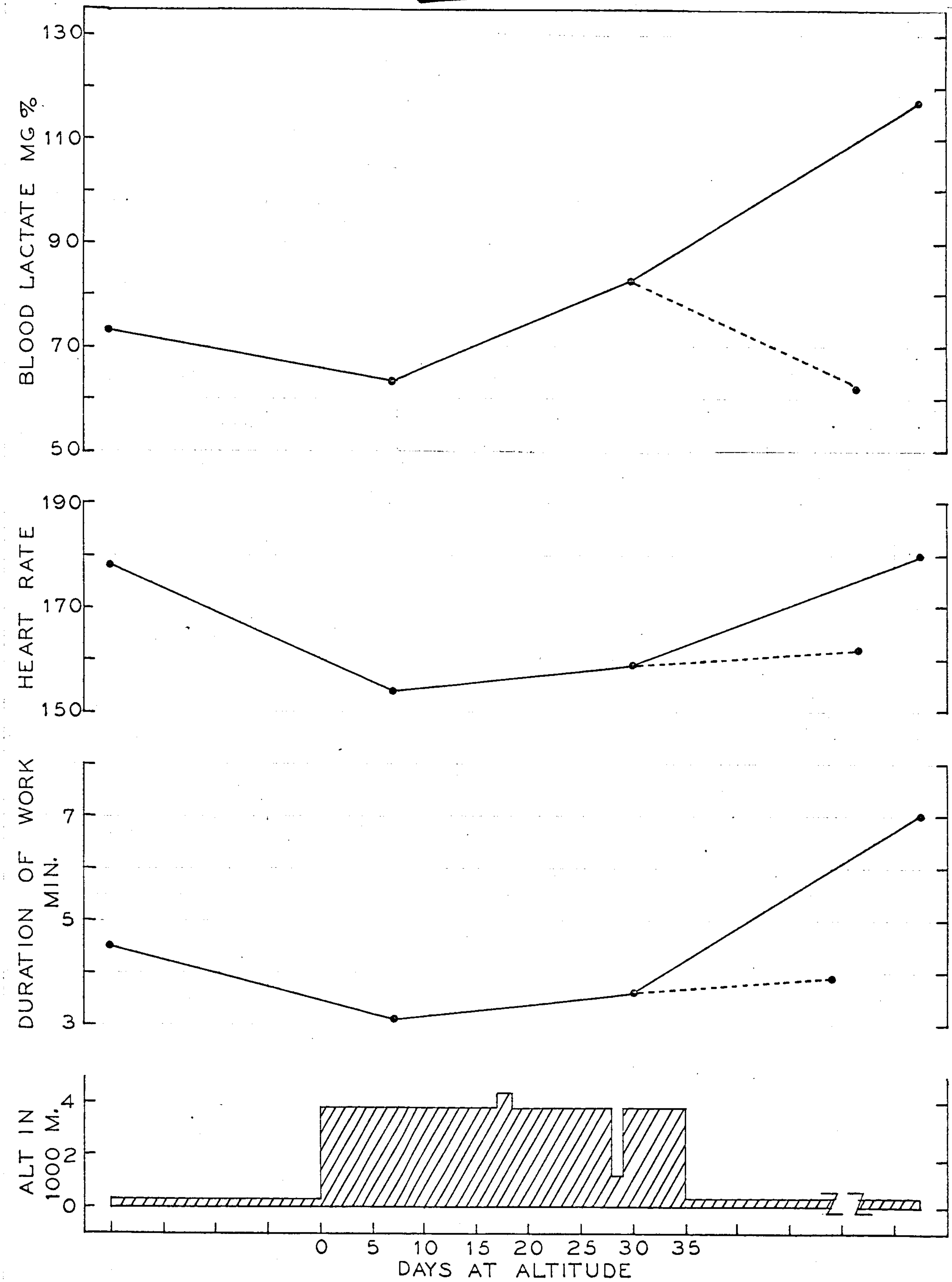


Figure 2. Average values of blood lactate, heart rate, and duration of work of the four men in experiments described in Fig. 1.

[redacted]



trained runners increase their work capacity on the bicycle ergometer, but by the 48th day at altitude some even surpassed their prealtitude values. We interpret this as an improvement in the efficiency of the men in bicycle work similar to that shown by our subjects. In the present study the average blood lactate concentrations following the exhausting bicycle work experiments increased from 63 to 82 mg% during the stay at altitude and this was associated with, and probably provided the stimulus for, a 17% increase in pulmonary ventilation ($\dot{V}_E$ max at STPD) during the exhausting work. It is interesting that the increased ventilation was not accompanied by some increase in $\dot{V}_{O_2}$ max and this indicates that even at high altitude pulmonary ventilation was not a limiting factor in determining the maximal O_2 consumptions of the men in work. The average HR max increased only slightly during the 5-weeks at 3800 m. This indicates that reduced cardiac output may be the principal factor limiting $\dot{V}_{O_2}$ max at altitude, particularly since Pugh (10) has found that a reduction of maximal heart rate at altitude is accompanied by a reduction in maximal heart output.

Following the return from the mountain to Bloomington the average maximal values of the men's $\dot{V}_{O_2}$, O_2 debt, blood lactate and $\dot{V}_E$ (STPD) in the exhausting work experiments were greater by 41, 10, 42 and 49% respectively than the values observed near the end of the 5-week sojourn at altitude (Table 2 and Figs. 1 and 2). Compared with the original prealtitude controls, these postaltitude maximal values for $\dot{V}_{O_2}$, O_2 debt, blood lactate and $\dot{V}_E$ (STPD) were greater by 16, 16, 58 and 33% respectively. As a result of, and in line with these substantial increases, maximal performance times for a fixed rate of work in the postaltitude experiments were much greater than those observed in either the altitude or the prealtitude experiments. The average HR max observed at Bloomington following the sojourn on the mountain were about the same as the original prealtitude control values.

Following descent exact repititions at Bloomington of the rate and time of the work performed in the final exhausting experiments at altitude were not exhausting for the men because the average $\dot{V}_{O_2}$ was higher than at altitude but still, except for SR, considerably below their maximal capacities at the lower altitude. Lactate and O_2 debt were much lower than the high altitude values for these experiments in all subjects except LM, who was recovering from a gastrointestinal infection contracted during the last days on the mountain. The increase in $\dot{V}_{O_2}$ in exact repititions at Bloomington of the experiments on the mountain were due to increased O_2 saturation of arterial blood, and hence increased O_2 supply to the skeletal and cardiac muscles. Heart rates were about the same at Bloomington as the subnormal maximal rates in the exhausting work at altitude, indicating greater stroke volume.

<u>Treadmill experiments</u>. Upon returning to Bloomington from White Mountain the men showed improvements in performance of work on the treadmill similar to their improvement in performance on the bicycle ergometer (Tables 2 and 3). Exact repititions by two of the men of the rates and times of the treadmill runs which exhausted them at altitude were not exhausting at Bloomington. The average $\dot{V}_{O_2}$ in these runs was about the same as at altitude, but values of lung ventilation, blood lactate and O_2 debt were even more reduced in these experiments at Bloomington than they were in exact repititions of the bicycle experiments as performed on the Mountain.

Since repeating the runs which had exhausted them at White Mountain did not exhaust them at Bloomington, experiments were carried out at the lower altitude in which the men performed harder runs on the treadmill and continued to exhaustion (Table 3). In these exhausting runs they demonstrated marked improvements in work capacity, associated with average increments of 35, 52, 40 and 40% in $\dot{V}_{O_2}$ max, O_2 debt, blood lactate and $\dot{V}_E$ max (STPD) respectively over values observed on them in the exhausting treadmill runs on White Mountain. These increments are comparable with those shown in the exhausting bicycle experiments after returning to Bloomington, except that the increase in maximal O_2 debt was greater in the treadmill experiments. This

Table 2. Responses of 4 men in oxygen debt experiments performed on a bicycle ergometer at Bloomington (264 m) and at various times during 5 weeks at Barcroft Laboratory, White Mountain (3800 m)

Subject	Work kpm/min	Work min	$\dot{V}_E$ max, l./min STPD	$\dot{V}_E$ max, l./min BTPS	$\dot{V}_{O_2}$ max l./min	O_2 debt, liters det *	O_2 debt, liters est. **	Lactate mg %	HR max
Control at 264 m									
SR	900	4.0	76.4	95.1	1.96	3.08	3.37	73.7	172
LM	1500	4.0	70.9	88.2	3.22	5.46	5.00	67.2	196
JN	1050	4.0	61.2	76.1	2.55	4.44	4.41	83.7	168
RG	1350	6.0	83.6	104.1	3.32	4.21	4.91	70.2	175
Average	1200	4.5	74.5	92.8	2.76	4.30	4.42	73.7	178
3-10 days at 3800 m									
SR	900	3.0	49.6	97.2	1.51	3.28	3.30	71.2	155
LM	1500	2.5	49.9	97.8	2.53	4.85	4.32	63.0	169
JN	1050	3.0	51.5	100.9	1.97	5.03	3.51	56.0	142
RG	1350	4.0	77.9	152.6	2.98	5.01	5.43	63.4	160
Average	1200	3.1	57.2	112.1	2.24	4.34	4.14	63.4	154
24-35 days at 3800 m									
SR	900	3.5	56.2	110.0	1.39	4.73	4.14	76.0	143
LM	1500	3.0	59.1	115.7	2.51	5.72	5.18	75.2	167
JN	1050	4.0	65.8	128.9	2.15	4.64	4.16	95.2	158
RG	1350	4.0	86.4	169.2	3.01	5.40	4.46	83.1	165
Average	1200	3.6	66.9	131.1	2.27	4.54	4.49	82.4	159
10-17 days after return to 264 m ***									
SR	900	3.5	68.8	85.7	1.96	3.12	2.51	58.4	145
LM	1500	3.0	68.3	85.0	2.81	6.52	5.16	77.2	176
JN	1050	5.0	67.5	84.0	2.34	3.47	3.14	71.6	161
RG	1350	4.0	87.2	108.6	3.21	4.65	3.83	40.2	164
Average	1200	3.9	73.0	90.8	2.58	4.43	3.66	61.9	162
More than 17 days after return to 264 m									
SR	900	6.0	86.0	107.1	1.90	3.43	4.58	127.6	168
LM	1500	6.5	97.1	120.9	3.75	6.70	6.01	132.6	198
JN	1050	6.5	100.3	124.9	3.32	4.70	3.39	115.0	175
RG	1350	9.0	112.3	118.5	3.80	5.14	6.82	91.4	180
Average	1200	7.0	98.9	117.8	3.19	5.00	5.20	116.7	180

* Determined oxygen debt

** Estimated oxygen debt

*** This experiment was a repetition of each subject's best performance at altitude; all other work bouts were continued to complete exhaustion.

[redacted]

is probably due to the fact that the O_2 debts following the treadmill runs were determined with the subjects resting during recovery, while they exercised aerobically during recovery in the bicycle experiments. Data in part II of this report show that the O_2 debt is lower if subjects exercise at a constant aerobic rate during recovery.

The increments in blood lactate following the runs at Bloomington as compared with the values observed at altitude confirm Klausen's (9) results reported in part VIII of this report and are in line with the results of Edwards (6). This effect was probably not a training effect since the men were accustomed to treadmill work and had no practice in running from the time of the exhausting treadmill experiments on the Mountain and those after returning to Bloomington.

Reference

1. Balke, B., F. J. Nagle and J. Daniels. Altitude and Maximum Performance in Work and Sports Activity. J. Am. Med. Assoc. 194:176-179, 1965.

2. Balke, B., J. G. Wells, and J. P. Ellis. Effects of Altitude Acclimatization on Work Capacity. Fed. Proc. 15:7, 1956.

3. Buskirk, E. R., J. Kollias, E. Picon-Reatigue, R. Akers, E. Prokop and P. Baker. Preliminary report to the U. S. Army Research and Development Command on Contract DA 49-193-MD-2709.

4. Dill, D. B., H. T. Edwards, A. Fölling, S. A. Oberg, A. M. Pappenheimer, Jr., and J. H. Talbot. Adaptations of the Organism to Changes in Oxygen Pressure. J. of Physiol. 71:47-63, 1931.

5. Dill, D. B., S. Robinson, B. Balke and J. L. Newton. Work Tolerance: age and altitude. J. Appl. Physiol. 19:483-488, 1964.

6. Edwards, H. T. Lactic Acid in Rest and Work at High Altitude. Am. J. Physiol. 116:367-375, 1936.

7. Elsner, R. W., A. Bolstad, and C. Forno. Maximum Oxygen Consumption of Peruvian Indians Native to High Altitude. In: The Physiological Effects of High Altitude. New York, Macmillan, 1964, pp. 217-223.

8. Gisolfi, C., S. Robinson and E. S. Turrell. Effects of Aerobic Work Performed During Recovery from Exhausting Work. J. Appl. Physiol. 21:1767-1772, 1966.

9. Klausen, K., S. Robinson, E. D. Michael and L. G. Effect of High Altitude on Maximal Working Capacity. J. Appl. Physiol. 21:1191-1194, 1966.

10. Pugh, L. G. C. E., Animals in High Altitude: Man Above 5,000 Meters-Mountain Exploration. In: Handbook of Physiology, Adaptation to the Environment. Washington D.C.: Am. Physiol. Soc. 1964, Sect. 4.Chap. 55, p.8

11. Scholz, R. H. H. Schmitz, T. Bucher and J. O. Lampen. Uber die Wi kung von Mystatin and Bäckerkefe. Biochem. Z. 331:71-86, 1959.

12. Velasquez, Tulio. Response to Physical Activity During Adaptation to Altitude In: The Physiological Effects of High Altitude. New York, MacMillan, 1964, pp. 289-300.