2 of 3

AD 603 932

WORK TOLERANCE: AGE AND ALTITUDE

9 p
hc - 1.00
mf - 0.50

D. B. DILL, Ph.D.
S. ROBINSON, Ph.D.
J. L. NEWTON, M.S.
Department of Anatomy and Physiology
Indiana University, Bloomington, Indiana

B. BALKE, M.D.
Biodynamics Branch

63-33

FEDERAL AVIATION AGENCY
CIVIL AEROMEDICAL RESEARCH INSTITUTE
AERONAUTICAL CENTER
OKLAHOMA CITY, OKLAHOMA
DECEMBER 1963

WORK TOLERANCE: AGE AND ALTITUDE

D. B. DILL, Ph.D.
S. ROBINSON, Ph.D.
J. L. NEWTON, M.S.
B. BALKE, M.D.

It is a curious fact that the unpleasant experiences during the first days at high altitude are most manifest when metabolism is lowest — in sleep — and when it is highest — in strenuous exercise. Sleep is interrupted by Cheyne-Stokes breathing; morning may find one with headache and nausea. Then if one attempts to climb or even walk briskly there may be cardiac distress, and certainly will be breathlessness and hyperventilation. In a few days however exercise becomes more tolerable and within a week climbing is apt to become a pleasure. Some will nod their heads in assent to the above statement but others will consider it ridiculous. This is understandable: there are a great many factors that affect the onset and degree of mountain sickness. Among these are the rate and nature of the ascent, the altitude reached, the age and fitness of the individual and his individual susceptibility. While physiologists have learned much about the physiological and biochemical changes that accompany adaptation to high altitude they cannot answer the question: why does one man adapt more rapidly and more completely than another? It was to learn more about this problem that we undertook in the Summer of 1962, a study of adaptation to high altitude as related to age. Several aspects of the study have been described ([1 2 3 4 5]); in this paper special attention will be given to work tolerance.

Methods:

The subjects were studied near sea level a few months before or several months after the altitude studies. One or both of two types of experiments were employed in assessing the capacity for oxygen supply. In one the treadmill was set at a grade of 9%. While walking 15 min at 94 m min on this grade metabolic rate was measured. This bout was followed by a 10-minute recovery period and then by a run on the same grade at the rate of 124, 156 or 188 m per min — depending on the estimated capability of the subject. For the run a 5-liter mixing chamber was interposed near the inlet to the gasometer; this was flushed out by the subject with expired air before he started running. Gasometer gauge readings were taken every 15 seconds and gas samples were drawn from the mixing chamber into 50-ml syringes for analysis on the Haldane apparatus. The first sample was drawn over the first half-minute, the second in the second half-minute and then one each minute through the fifth minute if the subject could run that long. An example of this type of experiment is found in Table 1.

In the other type of experiment the work rate was increased minute-by-minute either by increasing the grade of the treadmill or by adding to the brake load on the ergometer. Respiratory volumes were measured and gas samples collected and analyzed as described above. Or,

Research Supported in part by FA Contract #2049

Time min	V_{STPD} l/min	CO_2 %	O_2 %	VCO_2 ml/min	VO_2 ml/min	Heart rate
0 Start						
½	27.3	3.87	16.74	1050	1170	126
1	28.1	4.35	15.94	1220	1450	144
2	56.3	5.00	15.78	2800	2920	160
3	66.2	4.88	16.71	3210	2670	165
3½ Stop	71.4	4.72	16.91	3350	2730	170

TABLE 1: Typical treadmill run: W. H. Forbes, October 17, 1961, P_B 741 mm; t = 25° C; wt. 69 kg; ht 178 cm; rate 156 m/min; grade 9%.

expired air was collected in Douglas bags during the last few minutes. The monitored heart rate and blood pressure enabled one to judge when the subject was approaching his limit and when the collection of samples should begin. A comparison of these and other methods for assessing work performance has been reported by Newton.(6)

The subjects on whom work capacity was measured were Dill, Forbes, Balke, Talbott, Keys, McFarland and Robinson with age ranges of 54 to 71 and Terman and Newton, ages 23 and 27, respectively. Our primary interest was in observations in the basal state. Exercise studies were only carried out when they did not interfere with the objective of making observations in the basal state.

Results:

Table 2 includes observations on Dill during the five weeks at altitude in 1962, observations at high altitude in 1929(7) and in 1935, plus contemporaneous sea level observations in each case. In 1962 the peak oxygen intakes at altitude, relative to the value of 2010 ml/min at sea level, were as follows:

on day	at the altitude of	per cent (1935)
2	9,500 feet	87 (80)
10-20	12,500 feet	76 (69)
28	14,200 feet	73 (77)
34	12,500 feet	86

Date	Expt	P_B mm Hg	V_{STPD} l/min	V_{BTPS} l/min	R.Q.	VCO_2 ml/min	VO_2 ml/min	Blood Lactate mg %	Heart Rate	Blood Pressure
12-3-28	T	760	86.5	104.7	1.09	3580	3290	77		
5-2-29	E	750	69.0	84.7	1.05	2760	2620	77		
7-5-29	E	526	56.0	100.9	1.04	2190	2110		152	158/95
4-17-35	T	750	85.8	105.3	1.16	3520	3040		167	
1935	E	543	59	103			2440			
1935	E	489	46	90			2100			
1935	E	429	55	124			2340			
11-16-61	E	733	60.2	75.7	1.16	2280	1960	80	148	175/95
6-30-62	E	535	40.8	72.2	1.04	1820	1740		134	172/90
7-6-62	E	485	37.2	72.0	1.20	1660	1380		118	170/90
7-7-62	E	485	34.4	67.1	1.08	1650	1530		116	170/100
7-17-62	E	485	37.0	72.8	1.00	1540	1530	35	115	170/85
7-25-62	E	455	35.6	75.2	1.05	1540	1470	28	120	190/100
7-31-62	E	490	38.7	75.4	1.03	1790	1730	43	120	175/88
8-7-62	E	762	61.5	74.2	1.10	2280	2070		135	
8-22-62	E	737	58.5	73.2	1.03	2080	2010		142	162/75

T = Treadmill
E = Ergometer (Bicycle)

TABLE 2: Exercise tolerance at sea level and at altitude: Dill, summer of 1962: wt 72 kg; ht 178 cm; age 71.

These results show that even at the age of 71 sufficiently high demands can cause an augmentation of the capacity to cope more efficiently with stress situations: a relatively short stay at the physiologically more demanding altitude of 14,200 feet was followed by a marked improvement of work capacity at the lower elevation of 12,500 feet at which no progress had been made during a period of almost two weeks.

Although, in 1962, work capacity at sea level was only 66 per cent, and at an elevation of 9500 feet, only 71 per cent of that in 1935, the relative losses of work capacity with increasing altitudes were nearly the same in both years (see the bracketed values in tabulation above).

Observations on Talbott are summarized in Table 3A. Some of these observations are from unpublished fatigue laboratory records; those of 1935 are from Christensen ([8]). The maximum oxygen intake capacity at age 26 was 3930 ml/min, at 34 years of age 2910 ml/min (or 74% of the former) and at age 60 it was 2510 ml/min (or 64% of the value 34 years ago). In 1935 work capacity dropped at an altitude of 9500 feet to 74 per cent of that shown at sea level, at 12,500 it was 75 per cent, and at 15,000 feet 85 per cent of the sea level value. This relative improvement at the higher altitude was probably due to a physical training effect. In 1962, on the third day at altitude (12,500 feet) his maximum oxygen intake on the bicycle ergometer was 56 per cent of his sea level maximum on the treadmill. Both the peak values at sea level and at altitude in 1962 were 64 per cent of the comparable values in 1935.

Forbes and Keys had good records at high altitude in 1935 as shown in Table 3B and 3C. The data reported by Christensen ([8]) lack records of the maximum oxygen intake at sea level. Assuming an average decrease in peak

Date	Expt	P_B mm Hg	V_{STPD} l/min	V_{BTPS} l/min	R.Q.	VCO_2 ml/min	VO_2 ml/min	Blood Lactate mg %	Heart Rate	Blood Pressure
A. Talbott; summer of 1962; wt 74 kg; ht 173 cm; age 60										
12-10-28	T	760	117	142	0.99	3900	3930	82		
4-30-29	E	759	85	103	0.94	2560	2700	64		
7-25-29	E	523	72	131	0.99	2150	2170	66	152	132/90
1935	E	543	43	75			2170			
1935	E	489	45	88			2200			
1935	E	429	54.5	123			2470			
12-18-36	T	764	99	119	1.34	3900	2910	70	189	164/66
5-12-62	T	742	92	114	1.42	3580	2510	72	180	184/104
7-23-62	E	490	32.3	62.9	1.15	1610	1400	27	152	205/126
B. Forbes; summer of 1962: wt 71 kg; ht 178 cm; age 69										
1935	E	543	54	95			2500			
1935	E	429	42.5	96			2080			
1935	E	401	38	93			1850			
10-17-61	T	741	71.4	89.0	1.22	3350	2730	99	170	150/80
6-30-62	E	535	43.7	77.2	0.96	2100	2170		152	180/90
7-6-62	E	491	37.4	72.4	1.09	2000	1830		130	185/100
C. Keys; summer of 1962: wt 72 kg; ht 172 cm; age 59										
1935	E	543	51	89			2580			
1935	E	489	43.3	85			2100			
1935	E	429	53	120			2100			
1935	E	401	20	49			1100			
7-23-62	E	490	25.6	50.0	1.05	1160	1110		124	202/92
5-5-63	E	736	39.9	50.0	1.12	1420	1270		152	162/88

TABLE 3: Exercise tolerance at sea level and at altitude.

oxygen intake of about 85 per cent in going from sea level to an altitude of 9,500 feet, the respective sea level values would have been 2940 ml/min for Forbes and 3030 ml/min for Keys. The records of 1962 indicate that Forbes had nearly maintained that level of "physical fitness" while Keys had dropped to almost two-fifths of his original work capacity. At altitude, therefore, the work capacity of the 10-year older Forbes surpassed that of Keys markedly.

The most complete record of maximum performances is that of Balke (see Table 4). In 1944 when his sea level maximum was 3910 ml of oxygen per minute he reached 3540 ml/min at an elevation of 10,000 feet. Eighteen years later when his sea level maximum was 3440 ml/min the maximum oxygen intake was 2730 ml/min after a few days at 12,600 feet and two weeks later 2805 ml/min on the second day at 14,200 feet.

Date	Expt	P_B mm Hg	V_{STPD} l/min	V_{BTPS} l/min	R.Q.	VCO_2 ml/min	VO_2 ml/min	Heart Rate	Blood Pressure	Notes
8-3-44	E	709	74.9	97.7	1.05	3860	3670	188	210/56	active but untrained
8-20-44	E	706	90.8	119	1.01	3950	3910	184	215/65	in-training
8-26-44	E	540	94.5	165	1.08	3640	3390	176	210/75	2 days at alt.
9-11-44	E	540	102.0	179	1.27	4480	3540	180	200/70	3 weeks at alt.
5-26-55	E	745	104.2	130	1.06	4230	3990	180	200/45	in-training
6-2-55	E	446	60.7	131.3	1.07	2875	2700	178	190/65	Chamber
6-23-55	T	740	112.2	139	1.07	4380	4080	188	190/65	in-training
7-11-55	E	455	80.2	170	1.11	3280	2960	174	190/65	3 days at alt.
7-28-55	E	455	77.4	164	1.13	3320	2925	164	200/65	3 weeks at alt.
8-18-55	E	455	79.5	170	1.13	3160	2805	164	195/80	6 weeks at alt.
8-11-56	T	445	64.4	139	1.12	3000	2680	168	220/60	2 weeks at alt.
6-13-62	T	733	100.8	126	1.12	3840	3440	168	214/75	un-trained
7-9-62	E	488	66.4	130	1.04	2855	2730	160	225/85	2 days at alt.*
7-24-62	E	455	63.9	133.5	1.01	2830	2805	150		2 days at alt.**

*Following about two weeks at P_B 535
**Following about four weeks at P_B 535 or 488

TABLE 4: Exercise tolerance at sea level and at altitude: Balke, Summer of 1962: wt 74 kg; ht 182 cm; age 54.

Finally, Table 5 includes records of four who had had no previous measurements at altitude. In each case maximum performance was assessed at sea level on both the treadmill and ergometer. After only 2 days at the 12,500 foot level Robinson reached 59% of his sea level record on the ergometer; 9 days later he reached 70%. Newton after about 5 weeks at this altitude reached 66% while Terman after 7 weeks attained 83% of his capacity on the ergometer at sea level. At sea level Robinson and Terman attained higher levels of oxygen intake on the treadmill than on the ergometer: 2700 vs 2170 for Robinson and 3650 for Terman. Based on these maxima the percentages attained at altitude were 56 for Robinson and 76 for Terman. After 3 days at the same altitude McFarland reached 56% of his sea level capacity.

Date	Expt	P_B mm Hg	V_{STPD} 1/min	V_{BTPS} 1/min	R.Q.	VCO_2 ml/min	VO_2 ml/min	Blood Lactate mg %	Heart Rate	Blood Pressure
A. Robinson; summer of 1962: wt 64 kg; ht 171 cm; age 59										
11-15-61	T	745	86.1	106.5	1.12	3210	2700	83	162	225/105
11-16-61	E	733	97.2	115.2	1.28	2770	2170	95	150	220/115
7-30-62	E	487	39.6	77.7	1.11	1440	1290	46	148	228/122
8-7-62	E	487	52.4	102.7	1.24	1880	1510	31	162	
B. Newton; summer of 1962: wt 106 kg; ht 183 cm; age 27										
11-15-61	T	745	70.1	86.6	1.09	3140	2880	55	185	205/80
11-16-61	E	733	91.5	108.4	1.17	3500	2980	82	184	200/90
7-30-62	E	488	45.5	89.1	1.14	2230	1960	24	152	212/110
C. Terman; summer of 1962: wt 75 kg; ht 188 cm; age 23										
2-26-62	T	737	86.1	107.7	1.05	3870	3650	94	196	180/80
2-1-62	E	741	94.0	116.9	1.12	3810	3380	98	192	180/100
8-7-62	E	487	71.0	139.2	1.15	3220	2790		161	
D. McFarland; summer of 1962: wt 97 kg; ht 192 cm; age 61										
7-13-62	E	488	24.9	49.3	0.92	1200	1300			185/100
7-13-62	E	488	26.9	53.0	0.99	1260	1270	27	144	192/?
3-27-63	E	739	55.7	69.5	1.01	2340	2310	17	136	180/75
3-27-63	T	739	49.7	62.0	0.94	2040	2160	13	130	180/82

TABLE 5: Exercise tolerance at sea level and at altitude.

Discussion:

We have found few records in the literature comparable in most respects to ours. One is that of Christensen [8]. On himself as subject when he was about 30 years old his sea level maximum was 3720 ml per min. In successive approximately 10-day stays at four altitudes his maxima were as follows:

Altitude Feet	P_B mm Hg	V_{BTPS} l/min	VO_2 ml/min	Heart rate
S.L.	760	129	3720	190
9,000	543	123	3020	170
12,000	489	108	2560	150
15,000	429	136	2190	135
17,000	401	90	1800	132

Hurtado [9] has assessed the capacity of Peruvians dwelling at Morococha (P_B 455, 4540 m) in terms of the performance of sailors at sea level. Ten men ran at 132.4 m/min on a grade of 11%. The high altitude dwellers surpassed the sailors in every respect: their mean tolerance time in this endurance run was 53 min vs 34 min for the sailors. The sailors were slightly less efficient: 1333 vs 1167 ml O_2/min x m^2 BSA. In another even more impressive performance 12 sea level athletes and 12 Morococha residents ran at 135.3 m/min on a grade of 18.9%. Again the high altitude residents proved superior despite the fact that their counterparts were athletes. The oxygen debt was greater in the athletes: evidently they had to rely more on anaerobic reserves than did the residents of Morococha.

Pugh [10] has reported observations on mountaineers of the 1960-61 Everest expedition. Their performance was as follows:

No.	Altitude feet	P_B mm Hg	V_{BTPS} l/min	VO_2 ml	Heart rate
6	S.L.	750	120	3400	192
5	14,500	440	165	2580	159
4	18,000	380	159	2140	144
4	21,000	340	169	1950	146
2	23,500	300	120	1400	135

Pugh remarks that the several months spent at a barometric pressure of 380 mm Hg resulted in some deterioration. Experiences of Chilean sulfur miners support his observation. As Keys has related [11], an attempt to establish a village at 5700 m near the mine failed. At the time of our visit the highest community was at 5340 m, P_B 400; it had been established many years before. The miners climbed each morning 300 or 400 meters to their place of work. Evidently the critical barometric pressure above which the long-range net effect is deterioration even for rugged mountaineers is between 400 and 380 mm Hg.

A few generalizations are warranted. The observations of Hurtado on residents at Morococha indicate that they were completely adapted to that altitude since they out-performed young men at sea level. Since in no case at lower and higher altitudes any of our oxygen consumptions in the Balke test did reach sea level values it follows that in this respect acclimatization is slow, taking months, perhaps years.

Does this capability have a genetic factor? This may well be the case although it is unlikely that the responsible genes are peculiar to the Indians of the Andes and to the inhabitants of central Asia. We found a high degree of adaptation among the miners at 5340 meters in Chile. Some at least had come from sea level. We were told that the first three days were critical; many quit during this period while most of those who stuck it out that long were able to continue. Thus, it seems likely that some have inherent characteristics favoring adaptation to high altitudes while others lack them.

Practical experience in mountain climbing expeditions also supports the idea that there is a wide range in ability to adapt; particularly in the rate of adaptation. For measuring the rate of adaptation it appears that two criteria are of most importance: the amount of restful sleep and the capacity for oxygen intake in maximum exercise. The importance of the former criterion, as far as our observations go, is a matter of conjecture. On the other hand, our measurements of maximum oxygen consumption reveal considerable individual differences in rate of adaptation. There was no common pattern of response; the following brief statement about each individual makes this clear. Balke, the most fit and the most experienced at altitude, had a VO_2 at sea level of 3440 ml/min at age 54. After two weeks chiefly at P_B 535 he reached 79% of this at 82% of his sea level maximum. Dill, the oldest, reached 87% of his sea level after four weeks at altitude and finally 86% at P_B 485 after five weeks at altitude. Talbott who exercises regularly, including skiing, was limited to 56% of his sea level maximum at P_B 485 after two days at altitude: the corresponding figure for McFarland was 56. Forbes after two days at P_B 537 reached 79% of his sea level maximum and a week later at P_B 485, 67%. Keys was not examined at sea level until 10 months after the altitude study. His sea level maximum was only 5% greater than his oxygen intake at P_B 485 after two days at altitude. The two young men after six to seven weeks at altitude performed the Balke test at P_B 485. Newton reached 66% of his sea level maximum on the treadmill and Terman, 77%. Part of the disparity between individuals can be attributed to the difference in performance in walking with step-wise increases in slope and on the ergometer with increments in brake load. This difference is small in the cases of Balke, Dill and Newton but large in the cases of Robinson and Terman.

The best performances at P_B 485 expressed in ml of oxygen per min and per kg, rated in the order of decreasing oxygen intake, are as follows:

Subject	Age	Days at altitude	ml O_2/min:kg
Balke	54	28	38*
Terman	23	44	37
Forbes	60	9	26
Robinson	59	10	24
Dill	71	33	24
Talbott	60	2	19
Newton	27	36	18
Keys	59	2	17
McFarland	61	3	14

*At P_B 455; all others at P_B 485.

In reaching maximum performance at altitude it is noteworthy that the volume of air breathed is as great or greater than in maximum performance at sea level, at least in the more fit subjects. Sometimes the volume decreases at the greatest altitude, e.g., Christensen, but not always, e.g., Pugh's mountaineers. The bellows system, aided by the lower air density, is adequate to move the same volume of air over a wide range of oxygen saturation of arterial blood.

While the ability to ventilate the lungs is not only unimpaired but might even be increased at high altitude there can be no doubt that the attainment of the maximum breathing capacity during work sets a limit to the amount of physical work to be tolerated. Generally, the simultaneous decline in maximum oxygen consumption should be accompanied by a decline in cardiac output. A decrease in heart rate, therefore, is usually observed with decreasing barometric pressure. At occasions, however, investigators have been puzzled by the drastic reduction of the maximum heart rate during exercise at high altitude. Generally, the decline in attainable oxygen consumption is relatively greater than the decline in heart rate. Here are two examples:

Subject	P_B	ml Vo_2/min	ml O_2/min:heart rate
Christensen	760	3720	19.6
Christensen	401	1800	13.6
Balke	753	3440	20.5
Balke	455	2805	18.7

In the light of our findings it is clear that neither does age bar successful adaptation to high altitude nor does youth insure a high degree of success.

ACKNOWLEDGEMENT

Our pleasant weeks at the laboratories of the White Mountain Research Station were made possible by Drs. Nello Pace and Raymond J. Hock and their staff. Drs. F. G. Hall, W. H. Forbes and Mr. James L. Terman assisted in the study.

REFERENCES

1. Dill, D. B.: Reunion at high altitude. *The Physiologist* 6:40-43, 1963.
2. Dill, D. B., W. H. Forbes, J. L. Newton, and J. W. Terman: Respiratory adaptations to high altitude as related to age. In press as a chapter in the volume, *Relations of Development and Aging*. Chas C. Thomas & Co., Springfield, Ill.
3. Terman, J. W. and J. L. Newton: Changes in arterial and alveolar gas tensions as related to altitude and age. In press, *J. Appl. Physiol., 1963.*
4. Dill, D. B., J. W. Terman, and F. G. Hall: Hemoglobin at high altitude as related to age. In press, *Clinical Chemistry*.
5. Dill, D. B.: Hypoxia: High altitudes revisited. In press, *Medicina Thoracalis*.
6. Newton, J. L.: The assessment of maximal oxygen intake. *J. Sports Med. and Physical Fitness*, 3:164, 1963.
7. Dill, D. B., H. T. Edwards, A. Folling, S. A. Oberg, A. M. Pappenheimer, Jr., and J. H. Talbott: Adaptations of the organism to changes in oxygen pressure, *J. Physiol.*, 71:47-63, 1931.
8. Christensen, E. H.: *Sauerstoffaufnahme und respiratorische* Functionen in grossen Hohen. *Skand. Arch. Physiol.*, 76:88-100, 1937.
9. Hurtado, A.: Animals in high altitudes: resident man. Chapt. 54 in *Adaptation to the Environment*, Washington, D. C.: Am. Physiol. Soc., 1964.
10. Pugh, L. C. G. E.: Animals in high altitudes: man above 5000 meters; mountain exploration. Chapt. 55 in *Adaptation to the Environment*, Washington, D. C., Am. Physiol. Soc., 1964.
11. Keys, A.: The physiology of life at high altitudes. The international expedition to Chile, 1935. *The Scientific Monthly*, 43:289-312, 1936.

U.S. GOVERNMENT PRINTING OFFICE . 1964 O—732-429