OXYGEN REQUIREMENTS FOR THERMOGENESIS DURING COLD ADAPTATION AT HIGH ALTITUDE

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Summary : Experiments were carried out in human subjects during winter months (D.B. Temp —5°C) at an altitude of 3,660 m (12,000 ft) in Ladakh, India, to explore the possibility of further reduction in oxygen utilization for thermogenesis during the non-shivering phase. Oxygen consumption for resting, bicycle ergometer activities, and field marching activities were measured on repeated cold exposures in reduced clothing spread over a period of 6—7 weeks. Basal oxygen consumption and maximal oxygen consumption of these subjects were also recorded. The basal O_2 consumption was initially increased significantly during winter at high altitude, while at the end of 7 weeks stay it was about the same as at sea level. Maximal O_2 consumption was significantly reduced at high altitude and did not improve even after 6-7 weeks stay, while work output during the maximal test showed some improvement. The oxygen requirement for thermogenesis reduced by change over from shivering to non-shivering; and further reduced significantly even during the non-shivering phase, on repeated exposures to cold. These findings bear special significance as the increased economy in oxygen utilization for work in cold at high altitude will reflect on better physical performance at high altitude.

Key Words : Chronic hypoxia cold acclimatization exercise work at altitude maximal oxygen consumption basal oxygen consumption non-shivering thermogenesis

Repeated exposure to cold environments brings about decrease in the 'extra oxygen requirement for thermogenesis. This economy is achieved by conversion of shivering thermogenesis into non-shivering thermogenesis (7, 8, 9). This economy in oxygen requirement for thermogenesis may not be of such potential importance at sea level, as under rarefied atmospheric conditions at high altitudes where sufficient oxygen may not be available for other functions. Even after adaptation of body to hypoxic conditions at higher altitudes, simultaneous exposure to cold requiring extra oxygen for thermogenesis, creates further stressful situation which may decrease physical efficiency. Present studies were, therefore, planned to determine whether it is possible to further bring down oxygen utilization for thermogenesis even after the non-shivering phase has been reached.

These experiments were performed at an altitude of 12,000 ft (3,660 m) in Ladakh, India during winter months. From military point of view, it was considered necessary to carry out these studies not only during resting state, but also under different controlled work load conditions in the laboratory as well as in the field.

MATERIALS AND METHODS

The study was carried out in three phases. The subjects selected, 20-30 years in age (mean 22.5 yrs), were healthy volunteers from Indian Army. They had no previous exposure to high altitudes and were born and brought up at almost sea level stations. Different subjects were selected for each phase of study. Prior to studies at high altitude (12,000 ft or 3,660 m above sea level) control data were recorded in Delhi which has an altitude of about 700 ft (220 m) above sea level. After completion of the sea level studies at Delhi, the subjects were rapidly transported to high altitude station, the time taken for this being about an hour.

Phase I.

This phase of study was undertaken during winter months (November-December) of 1968 on a group of 10 soldiers. Three levels of activities were selected : i) lying-resting, (ii) 150 kgm/min (grade 1) work load, and (iii) 250 kgm/min (grade 2) work load, on bicycle ergometer. All the 10 subjects were exposed to all these activities during various phases and then oxygen consumption estimated. At sea level measurements were made in the laboratory which had dry bulb temperature of 22°—25° C. After being taken to high altitude, they were first studied between 2nd-4th day of arrival inside centrally heated rooms, where they were kept for first 4 to 5 days. The second study was done on 5th or 6th day during outdoor cold exposure with temperature ranging between —5°C to 0°C. The subjects were allowed to wear only a cotton vest and a drawer. After this first study during cold exposure, these subjects were cold exposed twice a day in undergarments, for about 10 minutes each time. Subsequent studies on oxygen consumption during different levels of activities were made at weekly intervals for about 6 weeks. Beyond the experimental periods, the subjects were kept warm and comfortable, but not housed in centrally heated rooms.

The subsequent two phases of study were carried out by replacing bicycle ergometer exercises with field marching exercises with different loads. As it was not possible to carry out the initial experiments indoors, the studies were carried out in two phases; one during summer months and the other during winter months. Different subjects were used in these two phases.

Phases II (Summer):

This phase of study was carried out during July-August of 1970, on 21 subjects, divided into 3 equal groups of A, B and C. Each group was assigned a different level of outdoor activity: (i) sitting-resting (GROUP A), (ii) marching with 15 kg load on level ground at 4 km/hr (GROUP B), and (iii) marching with 32 kg load as in (ii) (GROUP C). The dress used during outdoor experiments was summer uniform.

Apart from oxygen consumption for respective levels of activity, all the Groups were also tested for their oxygen consumption in basal states under comfortable environmental conditions.

At sea level, the mean outdoor dry bulb temperature during the experiments carried out in the morning hours was 28°C. At the high altitude, the first set of estimations were carried out on the 5th or 6th day of arrival. The mean morning outdoor dry bulb temperature during their period of stay at high altitude was 15.5°C. The subjects were not housed in centrally heated accommodation during this period, instead they stayed in ordinary military barracks. The subjects were made to carry out their respective assigned activity daily for 2 hr 30 min in open environments. The marching groups covered a distance of 10 km on level ground during this period, with 10 min break after each hour of marching, while Group A (sitting-resting) remained outdoors for the same duration. The subsequent estimations were made at weekly intervals, over a total period of 4 weeks stay at the high altitude.

Phase III (Winter).

This phase of study was undertaken during January-March 1971. Three groups of subjects A, B and C, consisting of 11, 11 and 9 respectively, participated in these experiments. Each group was assigned a different level of activity which was similar to phase II. During outdoor experiments, the dress was normal winter uniform used in plains with additional protection for ears and hands.

In this phase of study, besides the basal and activity oxygen consumption, maximal oxygen consumption was also recorded. The maximal exercise was conducted on a stepping stool. The height of the stool and the stepping rates were so adjusted both at sea level as well as at high altitude, that none of the subjects could carry out the test for more than 4 minutes. Duplicate measurements were made by giving an additional 5 kg pack to insure maximal effort. This test was conducted in light dress under comfortable indoor conditions. The 3rd minute expired air samples were used for oxygen determination.

The sea level experiments at Delhi were carried out at a mean outdoor dry bulb temperature of 12.5°C, and repeated at the expiry of 1-2 weeks, during which period the subjects carried out daily field activity. At high altitude the outdoor experiments started on 6th or 7th day of arrival after being kept in ordinary military barracks. After the first study the subjects were made to carry out their respective assigned activity daily, while the subsequent estimations were carried out at weekly intervals over a period of 7 weeks. The mean outdoor dry bulb temperature during morning hours of experiment was —5.5°C. The basal and maximal oxygen consumption studies were recorded at fortnightly intervals inside a room.

The oxygen consumption in all experiments was determined by collecting expired air in Douglas bags which was subsequently analysed on Beckman Oxygen Analyzer, Model E_2.

RESULTS

Phase I :

The mean values for activity oxygen consumption for each level of activity are summarized in Table I, while Fig. 1 summarises percentage changes in oxygen utilisation on cold exposure at high altitude in comparison with activity at sea level. Under warm laboratory conditions after 2-4 days stay at high altitude, there was hardly any change in the oxygen consumption for all the three levels of activity, as compared to the corresponding values at sea level. On first cold exposure shivering observed was maximum during lying-resting condition and the oxygen consumption increased by 151% above the sea level value. During the two grades of exercise on cycle ergograph shivering was not of that severity, while the oxygen consumption increased by only 32 and 25% respectively. After one week of cold exposure, shivering decreased and so did the oxygen consumption. There was no shivering after 2 weeks exposure to cold during the two grades of activity while shivering persisted in lying-resting state for 3 weeks. There was a fall of 65, 87 and 110% respectively in the oxygen consumption during the three levels of activity after 2 weeks. During non-shivering phase, there was further drop in oxygen consumption in the case of lying-resting and grade 1 activity, so much so that these values not only approximated but were 3 and 13% respectively lower than the sea level values. In grade 2 activity, on the other hand, there was no further drop in oxygen consumption after the non-shivering state had been reached.

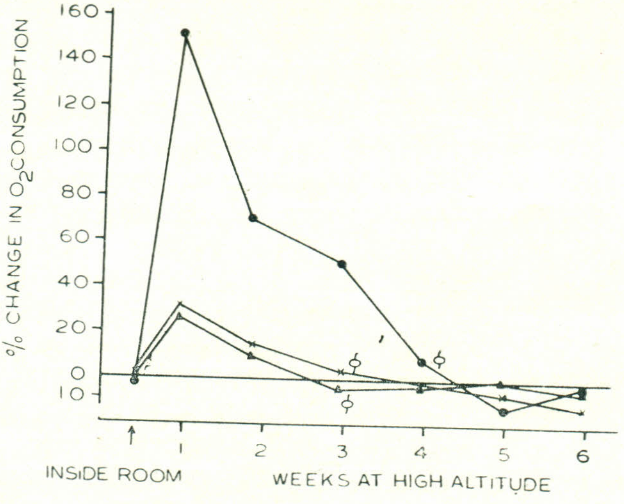

Fig. 1: Percentage change in oxygen consumption at high altitude during lying-resting (—●—) and activity on cycle ergograph with 150 kg m/min (—×—) and 250 kg m/min loads carried out initially inside a warm room (—▲—) and later on exposed to outdoor cold environment, as compared with oxygen utilization at sea level. § indicates stoppage of shivering response.

TABLE I: Oxygen consumption (ml/min STPD) during activity on cycle ergograph.

Activity	*At sea level inside room*	*Weeks at high altitude*						
		Inside heated room	*Exposed to cold environment*					
		0	1	2	3	4	5	6
Lying—resting	170	166	376	291	259	*186	149	165
150 kgm/min	485	474	640	558	*506	483	448	422
250 kgm/min	602	614	768	667	*579	587	595	580

The values are means obtained from 10 subjects
*indicates stoppage of shivering response.

Phase II (Summer):

The group mean values for basal oxygen consumption, measured indoors under comfortable conditions, and activity oxygen consumption, measured under outdoor conditions, are presented jointly with corresponding phase III (winter) values, in Tables II and III.

Basal oxygen consumption : As shown in Fig. 2, though the basal oxygen consumption for three groups, A, B and C decreased at high altitude on 5th-6th day by 10, 2 and

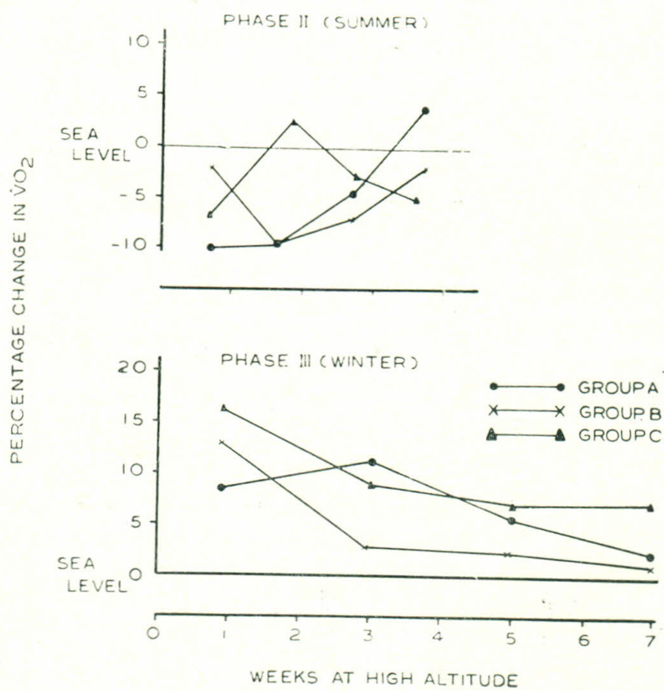

Fig. 2 : Percentage change in basal oxygen uptake during stay at high altitude inside a room, both during summer (Phase II) and winter (Phase III) as compared to basal oxygen uptake at sea level.

TABLE II : Basal oxygen consumption (ml/min STPD)

Groups	At sea level	Weeks at high altitutde						
		1	2	3	4	5	6	7
Phase II (Summer)								
A	175±16.7 (7)	158±14.5 (7)	159±20.0 (7)	167±11.8 (6)	183±13.0 (6)	—	—	—
B	175±7.9 (7)	171±10.5 (7)	160±18.1 (7)	163±15.8 (7)	171±9.7 (6)	—	—	—
C	175±22.0 (7)	164±20.0 (7)	170±18.6 (7)	170±12.4 (7)	166±9.5 (7)	—	—	—
Phase III (Winter)								
A	205±18.1 202±13.2 (11)	223±14.0 (11)	—	226±12.2 (11)	—	214±11.8 (11)	—	209±16.3 (11)
B	207±26.7 204±29.7 (11)	232±14.7 (11)	—	210±20.1 (11)	—	210±20.2 (11)	—	208±16.6 (11)
C	203±17.8 190±12.4 (9)	227±13.9 (9)	—	214±25.1 (9)	—	208±27.7 (9)	—	209±15.7 (9)

The values are group means with S.D. (±). The number of subjects studied is shown in parentheses. Basal oxygen consumption was measured under comfortable conditions in basal state inside a room.

TABLE III: Oxygen consumption (ml/min STPD) during field marching

Groups at Sea Level		Weeks at high altitude						
		1	2	3	4	5	6	7
Phase II (Summer)								
A Sitting Resting	227±13.5 (7)	226±20.9 (7)	207±23.9 (6)	219±17.6 (6)	211±13.6 (6)	—	—	—
B Marching (15 Kg. load)	624±50.7 (7)	803±87.8 (7)	663±77.0 (7)	605±55.5 (7)	597±61.0 (7)	—	—	—
C Marching (32 Kg. load)	804±47.5 (7)	977±84.2 (7)	859±96.4 (7)	865±55.9 (7)	825±42.4 (7)	—	—	—
Phase III (Winter)								
A Sitting Resting	247±13.2 249±15.6 248±14.7 (11)	351±39.8 (11)	304±31.6 (11)	300±40.3 *(11)	293±42.9 (11)	288±37.0 (11)	281±32.3 (11)	274±17.9 (11)
B Marching (15 Kg. load)	650±53.0 626±37.7 637±48.5 (11)	858±88.0 (11)	805±42.0 *(11)	806±46.5 (11)	789±47.9 (11)	804±41.9 (11)	785±58.9 (11)	763±46.0 (11)
C Marching (32 Kg. loazd)	826±61.5 824±70.5 816±41.7 (9)	1077±99.5 (9)	981±73.4 *(9)	969±95.1 (9)	926±45.4 (9)	921±45.8 (9)	946±47.3 (9)..	931±66.6 (9)

Values are means with S.D. (±). Number of subjects studied is shown in parantheses.
*indicates stoppage of shivering response (There was no shivering during summer).

6% respectively, the differences are not statistically significant from corresponding sea level values. Even after 4 weeks of stay, basal oxygen consumption did not show any significant difference from that measured at sea level in any of the groups.

Activity oxygen consumption: As illustrated in Fig. 3, group A (sitting-resting) did not show any significant change from sea level values, either on initial assessment or after 4 weeks stay at high altitude. On the other hand, the marching groups B (15 Kg load) and C (32 Kg load) increased their oxygen requirements by 29 and 21% respectively. This increase could be due to hypoxic stress as the environments were not cold enough to produce any shivering with summer clothing. This increase is statistically significant ($P < 0.01$). As the groups B and C carried out their daily activities at high altitude oxygen consumption decreased after one week. At the end of stay at high altitude, the differences in oxygen consumption from sea level values were not statistically significant.

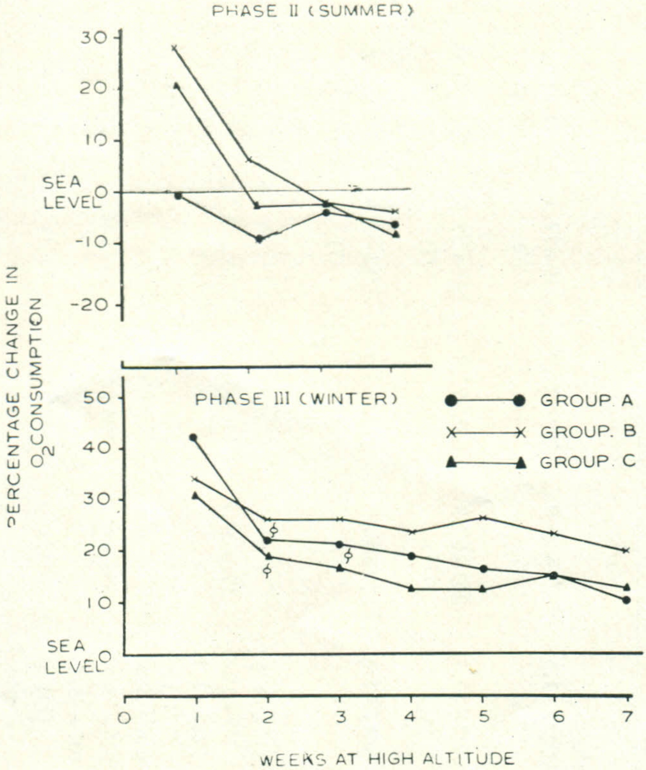

Fig. 3 : Percentage change in oxygen consumption during sitting-resting (group A) and field marching with 15 kg (Group B) and 32 kg (Group C) loads carried at high altitude during summer (Phase II) and winter (Phase III), as compared with oxygen utilization at seal level. § indicates stoppage of shivering response.

Phase III (Winter):

Basal oxygen consumption: It will be seen from Fig. 2 that the basal O_2 consumption at high altitude measured indoors under comfortable environmental conditions increased initially by 9, 13 and 16% respectively for groups A, B and C. These differences from corresponding sea level values are highly significant ($P < 0.01$). After about 7 weeks stay at high altitude basal 0_2 consumption values reduced significantly, and although still slightly higher than sea level values, these are not statistically different.

Activity oxygen consumption: Fig. 3 shows that O_2 consumption for all outdoor activities was increased above sea level values by 43, 35 and 31% respectively in groups A, B and C which were highly significant ($P < 0.01$). This increase was mainly due to shivering on first cold exposure. Maximum shivering was observed in Group A (sitting-resting). As the cold exposures were continued daily during outdoor activities with reduced clothing, there was decrease in O_2 consumption on second assessment by about 47% ($P < 0.01$), 24% ($P < 0.05$), and 38% ($P < 0.05$) respectively in Groups A, B and C. This significant decrease was due to decrease in shivering in group A (sitting-resting), and total disappearance of shivering in groups B and C. After two weeks, shivering disappeared completely in group A also resulting in a further decrease of 5% in their oxygen consumption. In subsequent non-shivering phases, maximum further reduction in O_2 consumption was recorded in the sitting-resting group (A) in which it decreased by about 50% at the end of 7 weeks (statistical significanee $P < 0.05$), Group B (15 kg load) showed a highly significant ($P < 0.01$) decrease of 24% during non-shivering phase, as compared to group C (32 kg load) which had a lower significant ($P < 0.05$) decrease of 31%. However oxygen utilization for all levels of activities in cold environment at high altitude remained higher than the corresponding sea level values by about 11, 20 and 13%, which is highly significant ($P < 0.01$).

Maximal oxygen consumption: The values and percentage change in maximal oxygen consumption at high altitude, as compared to sea level values, are shown in Table IV and Fig. 4. On first assessment at high altitude, the maximal O_2 consumption decreased almost uniformly in all the groups by about 21, 19 and 18% which are highly significant ($P < 0.01$). During and after about 7 week stay there was a slight improvement in some subjects which was statistically significant.

Work output: The work output was also computed during 3rd minute of maximal exercise by accounting positive as well as negative work rate. Negative work was taken as 1/3 of the positive work (15,16). These values are also shown in Table IV and Fig. 4. The work output also initially decreased at high altitude and its reduction was comparable to the reduction in maximal O_2 consumption, which was highly significant ($P < 0.01$). During subsequent weeks, although the work output showed some definite improvement which was statistically significant, it remained about 25% below the sea level values ($P < 0.01$).

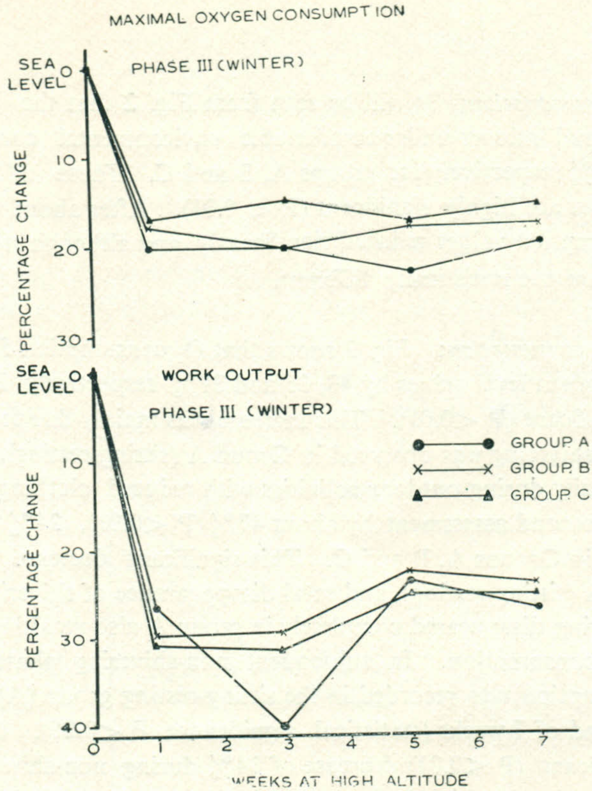

Fig. 4 : Percentage changes in maximal oxygen consumption and work output at high altitude with activity on a stepping stool carried out during winter (Phase III), as compared with the values at sea level.

DISCUSSION

Basal 0_2 *uptake :* Significantly increased BMR during first 3 days of stay at 4,300 *m* altitude has been reported by Grover (11). Surks (23) attributed this increase during the first week at high altitude to increase in plasma free thyroxine, though Grover himself did not obtain a clear thyroidal hyperactivity as judged by PBI estimations on his subjects. Consolazio et al (5), however, did not find any significant change in BMR in his subjects during a 3 week-stay at 3,475 *m* altitude, and suggested that increased BMR in Grover's subjects could be due to initial discomforts. The possibility of these observations being affected by sleeplessness, nausea, irritability and inability to lie on one's back due to Cheyne-Stokes breathing cannot be ruled out. The data presented in this study in Phase II (summer) and phase III (winter) were not influenced by such initial discomforts since the first set of observations were recorded only after 4-5 days of stay at high altitude.

In summer the values were not significantly different from the sea level values. During winter, however, the basal oxygen uptake increased significantly and was possibly the result

TABLE IV : Phase III (Winter):—Maximal oxygen consumption (ml/min/kg STPD) and work output (kgm/min)

Groups	*Sea level*	*Week at high altitude* 1	2	3	4	5	6	7
(*a*) *Maximal Oxygen Consumption*								
A	46±2.7 (11)	37±4.1 (11)	—	36.0±3.1 (11)	—	35±2.5 (11)	—	37±2.6 (11)
B	47±2.3 (11)	38±2.1 (11)	—	37±3.3 (11)		36±2.2 (11)		38±3.3 (11)
C	44±3.5 (9)	36±3.5 (9)	—	37±2.7 (9)	—	36±3.2 (9)	—	36±3.2 (9)
(*b*) *Work Output*								
A	1133±61.6 (11)	834±64.7 (11)	—	779±41.1 (11)	—	862±53.9 (11)	—	837±74.7 (11)
B	1109±53.5 (11)	779±61.4 (11)	—	782±69.3 (11)	—	860±72.4 (11)	—	845±74.7 (11)
C	1135±86.6 (9)	788∓70.9 (9)	—	780±43.6 (9)	—	850±87.3 (9)	—	851±67.9 (9)

Values are group means with S.D. (±). Number of subjects is shown in parentheses.

of cold environment. It could have been possible due to increased thyroidal activity as noted by Surks, or increased adrenomedullary activity as reported by Nello Pace et al (18). Over weeks of stay even in winter, the initial significant increase in basal O_2 uptake was reduced to levels not significantly different from values at sea level. This could be due to normalization of the increased endocrinal activity.

The increased BMR has been interpreted as a degree of natural acclimatization to altitudes in man by Gill and Pugh (12). Their scientific team personnel had increased BMR after 90 days stay at an altitude of 5,800 *m* (19,000 ft) but their BMR remained lower than that of Sherpas who were better acclimatized. Picon-Reategui (20) also found an increased BMR in native miners staying at an altitude of 14,900 ft.

Oxygen requirements for activities : It has been reported by several workers (4,5,13,21) that the oxygen consumption for bicycle ergometer activities at various loads, except near maximal, remains the same at higher altitudes as at sea level under laboratory conditions. An increased oxygen uptake for treadmill exercises has been reported by Consolazio et al (6). The resting O_2 consumption also does not change significantly. The data presented under Phase I of this study and measured under controlled temperature conditions inside a warm room are in agreement with these workers.

The sitting-resting O_2 consumption during phase II (summer) also did not change significantly from sea level values. Similar findings were also reported by Consolazio et al (5) at 3,475 m altitude. On the contrary, field marching with load increased oxygen consumption significantly at high altitude even during summer, when the environmental temperature was moderate. Similar findings have been reported by Nayar (17). This increased O_2 uptake during field marching in summer was significantly reduced within 3 weeks of continued daily activity and approximated the sea level values.

Under low environmental temperature conditions in winter, the oxygen requirements for all activities i.e. resting, activity on bicycle ergometer, and field marching with loads, increased substantially and significantly, and the extent of this increase depended on the degree of shivering. Davis (10), and Nishith et al (19) have reported an increased energy expenditure during outdoor activities at such altitudes when the environmental temperature was 4°*C*. His subjects, however, were suitably clothed and at the same time hobbling effect of garments on energy expenditure could not be ruled out. In Phase I of the present study minimum clothing, and in Phase III reduced fitting clothing was used. The increase in O_2 consumption was thus mainly due to the cold effect. It was further noted that the extra oxygen requirement for thermogenesis was significantly reduced with the disappearance of shivering, as also observed by Davis (7,8), and Davis and Johnston (9) in their cold acclimatization studies at sea level.

A very interesting observation based on the present study is that there is a further significant reduction in oxygen requirement for thermogenesis during the non-shivering phase on repeated exposures to cold at high altitude. Closer scrutiny of the results obtained during winter months indicates that the decrease in extra oxygen requirement was quicker in 250 *kgm/min* ergometer activity and 32 Kg load field marching activity, while a highly significant reduction was observed in 15 Kg field marching activity. Inspite of this, further significant reduction in oxygen requirements for activities during the non-shivering phase when exposed to cold environment, extra oxygen requirement for thermogenesis remains elevated above sea level values for similar activity levels as seen from Phase III data. From study of absolute values for 0_2 consumption during Phase I, it appears that oxygen utilization on repeated exposures to cold even tends to return to sea level values.

Maximal oxygen consumption : A significant decrease in maximal 0_2 consumption at high altitudes above 3,000 *m* has been a consistent finding of several studies (4,5,14,15, 21,22). However, there is no agreement on the extent of decrease due to variability in experimental methods, subjects and altitudes. The commonest form of maximal exercise test used has been on bicycle ergometer. In the present study a simple test of stepping up and down a steady stool was used and the result from this study are similar to others. Among the studies, uncomplicated by natural cold environments, Bushkirk et al (2) reported a small increase of 3% in maximal oxygen uptake of their subjects after 48 days stay at 4,000 *m* altitude. Most of the workers (5,13,15,21) have not been able to demonstrate a progressive increase in $V0_2$ *max* above 3,000 *m*. Saltin et al (22) suggested that failure of maximal 0_2 consumption to improve as ordinary altitude acclimatization progresses, is probably due to a lowered maximal cardiac output which decreases due to a lower stroke volume and also a lower maximum heart rate. The data from present study also suggest that probably no improvement in maximal oxygen consumption takes place at altitudes above 3,000 *m*, with or without cold acclimatization. Anderson (1) observed no improvement in aerobic capacity during cold acclimatization even at sea level by employing heavy training programme.

Work output : Work output decrease at high altitudes is also well documented (3,5,17), and is comparable to decrease in maximal 0_2 consumption. Consolazio et al (5) did not find any improvement in maximal work until exhaustion in his subjects during 20 days stay at an altitude of 3,475 *m*. The data presented here suggest that there is a significant improvement in work output, though work capacity remains lower than at sea level even after about 7 weeks. The improvement possibly may be due to improvement in neuromuscular coordination as a result of daily marching activity.

On the basis of the observations presented, it may be reasonable to conclude that :

(*a*) A short stay at high altitude does not bring about any significant change in the basal 0_2 consumption of sea level dwellers ;

(*b*) On repeated exposure to cold a significant reduction in extra oxygen utilization for thermogenesis takes place even during the non-shivering phase, though it still remains higher than non-cold exposure values. This could possibly be explained on the basis of normalization of endocrinal activities or due to decrease in the heat loss from body, on account of acclimatization.

and (*c*) Though there is no improvement in the aerobic capacity at high altitude, improvement in neuromuscular coordination as a result of daily activity results in improved work output.

These findings are of special strategic importance for high altitudes rather than for sea level cold acclimatization.

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