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Nutritional Aspects of High Altitude and Snow Bound Areas

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Abstract. The precise nutritional requirement of humans at high altitude area is not well defined. Further there are many conflicting reports on the effects of hypoxia on digestion, absorption and utilization of food at high altitude. In this review the nutritional requirements at high altitude and the effects of hypoxia on humans in relation to nutrition have been discussed.

1. Introduction

The stressful factors at high altitude (3000 m and above) from the physiological standpoint are reduced partial pressure of oxygen, cold temperature, intense solar radiations, high winds and difficult terrains. Besides, these areas are also arid in nature with sparse vegetation and potable water. The reduced partial pressure decreases the boiling point of water, thereby affecting sterilization and prepartion of food. All these factors give rise to nutritional problems.

In addition to the above natural constraints, an abrupt exposure of a sea level resident to higher terrestrial altitudes results in acute mountain sickness characterised by severe headache, lassitude and dizziness. Gastrointestinal disturbances, anorexia and vomiting are also encountered by many sojourners at high altitude. In the early phase of stay at high altitude the resultant anorexia leads to the reduction in food intake[1,3] by 25-30 per cent. As the voluntary intake of food is reduced, calorie deficit culminates into loss of body weight[1,3]; but in controlled studies with assurance of enough calorie intake by the subjects, Consolazia et al.[4] have shown no loss in body weight or state of hydration. Besides these problems altitude induced reduction in food utilization[5,7], poor tolerance to certain diet[3], increase in the rate of protein catabolism[8], disturbances in the water and electrolyte balances[9,10] are also well documented. Most of the studies are on an early phase of stay at high altitude. Further, precise recommendations on the nutritional requirements for soldiers at high altitude stations were scanty before the systematic studies by the Defence Institute of Physiology and Allied

Sciences, Delhi, Keeping in view the various controversies in literature regarding food utilization, energy requirement, nitrogen balance, body composition during prolonged stay at high altitude systematic studies both during the acute phase of induction to altitude and chronic exposure have been done from time-to-time under various projects. The results of some of these studies are discussed here.

2. Energy Requirement, Composition of Diet, Fluid and Electrolyte Balance

The calorie requirement in any particular environment is determined by the interaction of various factors like environmental temperature, activity level, and energy cost of various activities. Increase in energy expenditure ranging from 6.9 to 25 per cent have been reported by Johnson et al.[11] and Malhotra et al.[12] at high altitude. The energy expenditure for an adult (body weight 65 Kg) as determined by Malhotra et al.[12] at 3500 and 4300 m works out to 4205 and 4231 Kcal respectively. There is sufficient controversy regarding energy cost of various activities and basal metabolic rate at high altitude. If a person is adequately clothed to protect against extreme cold and exposed to a comfortable microclimate and the energy requirement is not unduly increased. Due to heavy clothing and its wobbling effect at high altitude, the energy cost of activities involving movement of individual increases, whereas, if the person is engaged in activities not involving movements like work on a bicycle ergometer, the energy cost at a fixed level of work is not different at high altitude and sea level. The energy expenditure at high altitude, referred to earlier, and the energy cost of various activities are shown in Tables 1 and 2.

This work had led to the recommendation of proper scales for troops located at high altitude stations. Prior to this the scales for high altitude area were arbitrarily evolved leading to lot of wastage of food material.

At least in the initial stages of stay at high altitude, hypoxic environment imposes a restriction on the availability of oxygen at the cellular level. When one considers this, and the combustion of carbohydrate which yields 5.05 Kcal/lit of oxygen *vis-a-vis* that of fat (4.69 Kcal/lit), the superiority of high carbohydrate diet will be *vivid*. Taking this into consideration along with the dietary pattern of Indian population, sufficiently high amounts of carbohydrate is incorporated in the scales which contribute 61 per cent of the total energy. Moreover, there are other advantages of high carbohydrate diet like improvement in physical work capacity and mental efficiency as a result of increased pulmonary ventilation and diffusion capacity with elevated alveolar pressures[13-16]. It is also interesting to find that Consolazio et al.[17] by their well-controlled studies designed to assess the efficacy of various nutrients at altitude have established a minimal requirement of 320 g of carbohydrate per day for moderately active individuals. Experimental studies at Defence Research and Development Establishment, Gwalior by Purshottam et al.[18] on rats have also shown an increased altitude tolerance when the rats were fed a high carbohydrate diet of 75 per cent under severe hypoxia (4870 m). The normal experience of mountaineers and sojour-

Table 1. Mean time spent daily in various tasks and the energy expenditure

Activity	Energy cost of the task Kcal/min	1200 ft Time spent day hr mt	1200 ft Energy expenditure Kcal	1500 ft Time spent day hr mt	1500 ft Energy expenditure Kcal
1	2	3	4	5	6
Sleep	1.04	8 30	530	8 30	499
Washing and toilet	3.00	1 05	195	1 15	225
Easting	1.50	2 09	104	1 40	150
Line duty of sentry duty	2.50	0 36	90	0 48	120
Reading, writing & indoor games	2.20	1 40	220	1 08	150
Arms cleaning and training in firing practice	2.90	1 40	290	1 00	174
Trench digging	9.00	2 27	1323	—	—
Road work at 14500-16500 ft	7.25	—	—	2 49	1225
Rest in between work	1.45	2 57	257	3 17	286
Carrying load uphill (1/3 grad)	11.00	0 50	550	—	—
Climbing uphill slope (1/6.5) at 3 km/hr	8.50	—	—	1 20	680
Climbing down hill	4.50	0 20	90	0 43	194
Lightly moving about at 3.2 km/hr	4.40	1 46	466	2 00	528
Total		24 00	4205	24 00	4231

Table 2. Comparison of energy cost at different altitudes at sea level and at high altitude

Activity	Oxygen cost of exercise (1/min) Sea level	Oxygen cost of exercise (1/min) 15000 ft
Sitting/resting	0.286	0.294
Standing (sentry duty)	0.480	0.500
Stepping up and down a stool and controlled rate	2.370	2.330
Working on bicycle ergometer (600 kgm/min)	1.460	1.400
Walking on level ground at 3.20 km/hr with appropriate clothing	0.560	0.980
Walking on a level ground at 5 km/hr (clothed)	0.920	1.350
Trench digging	1.450	1.800

ners who have a craving for sugar and sweets at altitude, though fortuitous, indirectly confirms the utility of high carbohydrate diets. The high altitude native's diet both at Andes and Himalayan ranges have a high carbohydrate content.

The literature regarding fluid balance at high altitude is highly controversial. Mild hypoxia induces polyuria but certain individuals become oliguric also during the first few hours of exposure to high altitude. Consolazio et al.[3] in one of their earlier studies have shown negative water balance in troops stationed at an altitude of 4300 m for four weeks. At an extreme altitude due to hyperventilation along with low humidity in the environment, a person becomes dehydrated. Krzywicki et al.[19] and Consolazio et al.[4] attribute the loss of body weight to voluntary dehydration. These authors also state that intracellular water is reduced while extracellular water remains constant. Bhardwaj and Malhotra[20] by anthropometric techniques and soft tissue X-ray of muscles have also shown a loss in water and bone mineral contents in humans after a stay of four weeks at an altitude of 4000 m. But this study lacks in dietary control. On the other hand, Sridharan et al.[21] have shown by controlled studies that there was no change in the fluid balance at an altitude of 3500 m when sufficient quantities of water by way of drinks was ensured. Salient findings of unchanged water balance are depicted in Table 3 as below.

After a prolonged stay at high altitude there is an increase in body water content of sea level residents as reported by Bhardwaj et at.[22]. No change in hydration and unaltered fluid balance could be attributed to an increase in intracellular water and redistribution of body fluids. Normal hydration levels without any evidence of loss of body water is also reported by Surks et al.[1] and Hannon et al.[23]. Hypohydration seems to be a transient state and returns to almost similar levels as seen in native populations such as in Andeans and Ladakhis[24]. Analysis of the carcasses of animals exposed to high altitude showed no change in body water content as reported by Schnakenberg et al.[5]. As thirst is not an accurate and proper guide for the need of water at high altitude and cold environments, there is a possibility of dehydration in the initial phases of sojourn. Therefore, to encourage fluid intake (at least 1.8 litres/day) by way of beverages, liberal amounts of tea leaves (14 g), sugar (120 g) and milk powder (36 g) are incorporated in the ration scales for troops stationed at high altitude.

As regards the electrolyte balance, increased urinary excretion of Na^+ and K^+ on exposure to hypoxia are reported by some workers[25,27], while others[28,29] have found only increase in Na^+ with decrease in K^+ excretion. Reports on the changes in the serum levels are still conflicting. Studies by Malhotra et al.[30] as well as Chatterji et al.[31] on the Indian troops have shown no significant change in serum Na^+ and K^+ levels. Chatterji et al.[31] at the same time have found decreased levels of magnesium and calcium excretion along with increased level in serum during acute hypoxic exposures in human at altitude of 3770 m. With adequate intake of electrolytes it is possible to achieve normal balance of most of the ions. The changes in Mg^{++} level when viewed with earlier studies in subarctic exposure of men by Mc-Aleese & Forbes et al.[32] and Hannon et al.[33] is interesting and requires further elucidation of the role of Mg^{++} and Ca^{++} ions in cold and hypoxic environment. Picon-Reategui.[34] has shown an increased absorption of calcium from the food by the natives of high altitude and attributes this to the increased ultra-violet radiation at high altitude which may increase the availability of vitamin D having a role in calcium metabolism.

At high altitude there is always a balance between the blood formation and destruction. There is no evidence to show any increased requirement of iron. It is

Table 3. Water balance at sea level (SL) and high altitude (HA) 3500 m

Place	Water gain (l)			Total (l)	Water loss			Total (l)	Water balance (l)	Body wt changes
	Fluid intake	From food	Metabolic		Urine	Skin &	Faeces			
SL	3.16 ±0.12	1.29 ±0.00	0.44 ±0.00	4.89 ±0.12	1.06 ±0.14	3.81 ±0.30	0.17 ±0.00	5.04 ±0.22	-0.15 ±0.18	−0.01 ±0.15
HA										
Day 1	1.87*** ±0.01	0.95*** ±0.02	0.30*** ±0.01	3.12*** ±0.12	1.79 ±0.13	1.36*** ±0.04	0.18 ±0.07	3.33*** ±0.20	−0.21 ±0.14	−0.21 ±0.15
Day 2	1.58*** ±0.11	0.96** ±0.06	0.35** ±0.02	2.89*** ±0.03	1.57 ±0.12	1.77*** ±0.11	0.20 ±0.04	3.54*** ±0.17	−0.65 ±0.13	−0.47 ±0.13
Day 3	1.44*** ±0.92	0.81** ±0.11	0.29*** ±0.01	2.54*** ±0.20	1.29 ±0.21	1.32*** ±0.16	0.17 ±0.03	2.76*** ±0.30	-0.22 ±0.27	−0.11 ±0.15
Day 4	1.94*** ±0.16	1.02** ±0.04	0.36* ±0.02	3.32*** ±0.20	1.79 ±0.22	1.23*** ±0.13	0.19 ±0.05	3.21*** ±0.24	+0.11 ±0.23	0.10 ±0.25
Day 5	2.29** ±0.36	0.78*** ±0.17	0.32*** ±0.03	3.39*** ±0.25	1.64 ±0.14	1.40*** ±0.27	0.18 ±0.07	3.22*** ±0.54	+0.17 ±0.16	0.17 ±0.20

***$p<0.001$; **$p<0.01$; *$p<0.05$

also well documented that 10 to 15 mg of iron along with the body stores could meet the needs of increased haemoglobin synthesis during the course of physiological readjustments, those take place at the time of early phase of altitude stay[35].

3. Vitamins

Vitamins are known to have a prominent role in oxidation-reduction processes in the metabolism in biological systems. The ascorbic acid requirement is thought to be increased due to stress induced enhancement of adreno-cortical activity. In addition to this, higher doses of vitamin C are also claimed to be beneficial to improve the physical performance. Due to logistic problems the supply of fresh vegetables and fruits is also limited at altitude. Earlier to the work of Verma et al.[36] the troops at altitude were authorised 300 mg of vitamin C. These authors have studied the vitamin C excretion levels in urine in well acclimatized troops at an altitude of 3500 m and found that even on 100 or 50 mg supplementation for two weeks, the excretion levels of vitamin C for 24 hours after a load dose of 400 mg was ranging as high as 93.3 to 307 mg and 72.1 to 302 mg respectively. Subsequently Sridharan et al.[37] have determined the levels of ascorbic acid both in plasma and leucocytes in subjects prior to induction to altitude at SL and after 10 to 30 days of stay at 4000 m. They found an interesting shift of plasma ascorbic acid to leucocytes at altitude. The intake of vitamin C in this study by the subjects was 45 mg at SL and 180 mg at HA. The decrement in the plasma ascorbic acid and better saturation of leucocytes at high altitude shows different turn over rates of this vitamin at altitude as compared to sea level. The data is presented in Talbe 4.

Table 4. Mean ($\pm$ SE) values of ascorbic acid in plasma and leucocytes at sea level and high altitude

	Plasma ascorbic acid μg/100 ml	Leucocyte ascorbic acid μg/10^8 cells	Ascorbic acid intake mg/day
SL	476.00 $\pm$ 48.66	17.33 $\pm$ 1.82	45
A_{10}	179.56 $\pm$ 30.84*	54.41 $\pm$ 3.58*	180
A_{30}	130.90 $\pm$ 11.22*	27.81 $\pm$ 1.76*	180

*$p < 0.001$
SL—sea level:
A_{10}—after 10 days stay at high altitude;
A_{30}—after 30 days stay at high altitude.

These two studies clearly indicate that supplementation beyond 100 mg of vitamin C at high altitude is superfluous. One of the interesting aspects of ascorbic acid nutrition is that altitude natives of Peru, consume a diet with ascorbic acid content ranging between 10.5 to 76.9 mg[38,39]. The requirements of other vitamins are not well established, but with the rations supplied at altitude no signs of deficiency diseases are reported[40].

The proximate composition and nutrient content in the ration scale currently in vogue are presented in Table 5.

Table 5. Nutrient content of the ration scale for troops stationed at 9000 ft and above

Nutrients	Quantity
Calories	4829 Kcal
Proteins	144 g
Animal proteins	39.85 g (27.67%)
Fats	147.9 g
Carbohydrates	746.8 g
Calories contributed by proteins	576 Kcal (11.72%)
Calories contributed by fat	1331.1 Kcal (27.22%)
Calories contributed by carbohydrates	2987.2 Kcal (61.06%)
Vitamin A	6279 i.u.
Thiamine	4.5 mg
Riboflavin	3.8 mg
Nicotinic acid	37.5 mg
Ascorbic	247.6 mg
Iron	91.5 mg
Calcium	1.55 g

4. Requirement of Protein at High Altitude

Negative nitrogen balance and a shift of protein from muscular to non-muscular regions in humans and in animals exposed to altitude (3000 to 5000 m) have been reported[41,43]. Negative nitrogen balance reported by Consolazio[42] and Surks et al.[43] was on intake of 50 to 60 g of protein/day. In both these studies calorie intake was less at altitude and there was a loss of body weight in the subjects. When the subjects are adequately nourished at high altitude this negative nitrogen balance is not seen[4]. Whitten et al.[44] show an altered ratio of total essential amino acid to total non-essential amino acids suggesting changes in the nitrogenous components of the serum as a result of changes in the protein metabolism which affects protein utilization. Defence Institute of Physiology and Allied Sciences, Delhi has carried out extensive studies on nitrogen metabolism both at the acute phase and after long term acclimatization. In well controlled study with an intake of about 12 g of nitrogen/day, Sridharan et al.[37] have shown positive balance of about 5 g. On the third day of stay at high altitude, similar values are also reported by Consolazio et al[4]. After prolonged stay of more than two years at altitude, the nitrogen utilization was not less than 85 per cent. The pattern of excretion of nitrogen at altitude[45] by human subjects after more than two years of stay is depicted in Table 6.

Table 6. Nitrogen excretion pattern at high altitude

Parameters	Sea level	11,500 ft	15,500 ft
Nitrogen intake	21.70	11.40	11.80
(g)	(18.0–23.0)	(8.4–14.6)	(9.61–10.33)
24 hrs urinary excretion of	13.5	9.1	7.38
Total nitrogen (g)	(12.0–18.0)	(7.9–11.8)	(6.4–8.5)
Urea nitrogen	11.5	5.56	5.78
(g)	(10.0–15.0)	(3.9–8.8)	(4.2–6.54)
Amino nitrogen	0.120	0.066	0.045
(g)	(0.100–0.150)	(0.045–0.090)	(0.033–0.06)
Ammonia nitrogen	0.565	0.584	0.461
(g)	(0.80–0.81)	(0.427–0.795)	(0.30–0.64)
Creatinine	1.27	1.27	1.23
(g)	(1.00–1.80)	(1.04–1.62)	(0.60–0.63)
Creatine	0.10	0.18	0.181
(g)	(0.00–0.20)	(0.13–0.24)	(0.083–0.262)

The variation in the serum protein levels studied on a longitudinal basis was also found to be within normal range. After 24 months of stay at high altitude it was found to be 7.18 g/100 ml[46]. With complete acclimatization no decrease in anaerobic capacity or muscle power was observed by Malhotra et al[47]. This finding justifies that after acclimatization there is no alteration in protein metabolism at altitude when intake of adequate food (4500 Kcal) along with protein at the level of 2 g/kg body wt/day was ensured.

5. Digestion and Absorption

In one of the expeditions in the Himalayan mountains, the pioneer scientist Pugh[48] has observed high losses of fat in stools. Pitmann and Cohen[49] have suggested a mal-absorption due to hypoxic effect on intestines. After acclimatization to altitude of 3800 m for two years, Rai et al.[50] have studied the utilization of fat, by feeding high levels of fat up to 320 g per day. In their studies they have found about 95.5 per cent of fat digestibility with almost constant levels of feacal fat.

The utility of high fat diet is of great importance as the troops at certain times, may have to do prolonged work under field conditions. During prolonged heavy exercise (80 per cent of maximal oxygen consumption) the muscle glycogen gets depleted very fast under cold conditions[51] and the subjects get exhausted. The concentrated form of energy as fat, is an advantage during exercise in field conditions at altitude and therefore the usage of high fat diet in specific situations is relevant. In normal rations at high altitude it is about 140 g and is well tolerated.

An attempt by Sridharan et al.[21] to clarify the gastrointestinal functions with specific tests such as D-xylose absorption, gastric acidity, pentagastrin stimulation test, peptic activity along with food utilization have also not indicated any adverse effect. In this study the basal and maximal gastric juice volume in sojourners at altitude, and high altitude natives, and altitude acclimatized sea level residents did not differ in any way, but the rate of acid production after pentagastrin stimulation showed a significant fall in all the three groups. The peptic activity was high on the second and the third day of stay at high altitude in sojourners but in the second week, only the maximal stimulated activity was higher in sojourners and there was no difference between the high altitude acclimatized individuals and the initial levels in sojourners at sea level. There was no significant difference in the D-xylose excretion levels at sea level and high altitude, signifying that the absorption from the intestine is not altered. The utilization of energy at altitude in the first week along with feacal fat losses and nitrogen balance for the first three days is reflected in Table 7.

Long term studies on carbohydrate metabolism by Srivastava et al.[52] have shown that the fasting blood sugar level was raised initially and remained high up to 10 months of stay of sea level residents at high altitude, thereafter it fell and was less than even the initial sea level values—the values being 76.4 ± 3.8, and sea level value of 97.6 ± 2.29 mg per cent respectively. The corresponding values for the high altitude natives (Ladakhis) were 86.4 ± 7.28 mg per 100 ml. The glucose tolerance remained normal throughout the stay at high altitude. The lower levels of blood glucose confirms the earlier observation of Picon-Reategui et al.[53].

Though reference to thyroid at this stage may not be fitting, it is to be noted that the problem af goitre in high altitude population, as a result of iodine deficiency, is of great importance. In sea level residents, during their stay at altitude, increased tendency of thyroid gland enlargement is also seen. But at the same time, the TSH levels and TRH response is not significantly altered at high altitude[54]. The thyroidal enlargement which occurs as a compensatory process if not associated with nodular changes, returns to normal levels on reinduction to sea level[40].

The effect of partial starvation after acclimatization to high altitude in sea level residents, should be studied more in depth as hypoxia is reported to suppress the dietary induced components of resting metabolism and decrease cold tolerance in the experimental animals[55]. This aspect is of significance as the troops in certain situations may have to go on long range patrol duties or may be cut of from the main base while guarding the frontiers at higher heights.

Table 7. Efficiency of food and fat utilization at sea level and altitude of 3, 500 m (values are mean ± SEM)

Parameter	Sea level	Day at altitude						
		1	2	3	4	5	6	7
Energy intake (MJ)	13.18 ±0.10	9.06*** ±0.12	10.55*** ±0.51	8.69*** ±0.89	10.81** 0.60	9.60*** ±0.40	9.02*** ±0.31	10.55*** ±0.38
Losses in faeces (MJ)	0.95 ±0.23	0.79 ±0.15	0.64 ±0.09	0.72 ±0.09	0.79 ±0.10	0.79 ±0.11	0.67 ±0.07	0.69 ±0.10
Utilisation (%)	92.68 ±1.79	91.38 ±1.54	93.79 ±0.89	92.85 ±0.99	92.62 ±0.89	91.62 ±1.34	92.57 ±0.78	93.41 ±0.83
Fat intake (g)	80.15 ±0.62	54.63*** ±0.53	66.61*** ±1.85	64.41* ±5.45	—	—	—	—
Faecal fat (g)	5.01 ±1.18	5.09 ±1.46	2.46 ±0.45	3.61 ±0.72	—	—	—	—
Utilisation (%)	93.68 ±1.52	90.67 ±2.71	96.28 ±0.70	94.50 ±0.96	—	—	—	—
Intake (g)	14.25 ±0.0	11.60*** ±0.51	12.77** ±0.51	12.13** ±0.75	—	—	—	—
Urinary excretion (g)	9.06 ±0.59	7.53 ±0.47	6.55** ±0.48	5.89*** ±0.46	—	—	—	—
Faecal excretion (g)	1.77 ±0.12	1.48 ±0.24	1.91 ±0.21	1.32 ±0.19	—	—	—	—
Total excretion (g)	10.83 ±0.61	9.01 ±0.58	8.46** ±0.44	7.21*** ±0.56	—	—	—	—
Balance (g)	3.40 ±0.61	2.59 ±0.98	4.31 ±0.62	4.91 ±0.33	—	—	—	—

*$p<0.05$

**$p<0.01$

***$p<0.001$

6. Conclusion

The abnormalities noted during certain scientific expeditions at high altitude like negative nitrogen balance, changes in serum albumin levels, amino acid levels, negative water balance and decreased fasting blood glucose levels, mimic the metabolic changes noted during the energy restriction. But after long term acclimatization, there seems to be no abnormality in the metabolic process without nutritional deficiencies when the energy intake at the rate of 4500 Kcals along with 140 g of protein is reckoned in highly active soldiers. In conclusion it may be said that seemingly abnormal metabolic changes during the acute phase of high altitude exposure could be attributed to anorexia with resultant deprivation of energy and nutrient intake, rather than the hypoxia *per se*.

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