

Energy and Water Balance at High Altitude

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Abstract

Many studies have shown that subjects lose significant amounts of body mass, fat mass as well as fat-free mass, during a climb to and/or a stay at high altitude. Altitude-induced weight loss is mainly caused by malnutrition due to hypoxia-related satiety, independent of acute mountain sickness.

Introduction

There is evidence that the altitude limit for the maintenance of body weight is ~5,000 m. For instance, Consolazio et al. (4) transported six healthy young men from sea level to 4,300 m for a 6-day period, supplying them with a constant diet of ~16 MJ/d, of which one-half was in liquid form and the remaining half in normal foods with a menu rotating after the third day. Overall mean body weight loss was only 1 kg and nitrogen balances were slightly positive, indicating that subjects did not lose muscle mass. Butterfield et al. (3) studied seven healthy men before and while they were subjected to a 3-week stay at 4,300 m, giving them access to the same diet at sea level and high altitude, increasing intake at high altitude to accommodate any increased needs. There was a mean body weight loss of 2.1 ± 1.0 kg over the 3-week period, but the rate of weight loss significantly diminished from 201 ± 75 g/day over the first week to 72 ± 48 g/day over the last week. Finally, during a 1-month stay at 5,050 m, it was shown that, in the presence of sufficient comfort and palatable food, weight loss could largely be prevented (7). The focus of this review will mainly be on studies at altitudes >5,000 m, where weight loss is remarkable, i.e., between 1 and 2 kg/wk, as a result of an energy imbalance of 4 to 8 MJ/day (10, 11, 14–16).

A disturbed energy and water balance can be caused by a reduction of intake, an increased requirement, or by both simultaneously. Accurate assessment of intake and expenditure is not an easy job, and studies at high altitude have limited access to laboratory facilities. An additional complication at high altitude is the confrontation with cold and stress as well as the frequent occurrence of acute mountain sickness (AMS). Tracer techniques like labeled water for the assessment of energy expenditure, water loss, and body composition can be applied under field conditions and have allowed new research in this area over the last 10 years. However, the number of studies is limited ([10](#), [11](#), [14–16](#)), one reason being because of the shortage of label (^{18}O).

▶ Energy expenditure

Daily energy expenditure can be divided into three components: basal metabolic rate, diet-induced energy expenditure, and physical activity-induced energy expenditure. Basal metabolic rate is normally the largest component of our daily energy expenditure. The main determinant of basal metabolic rate is body size, more specifically the active cell mass or fat-free mass. Diet-induced energy expenditure is a fixed proportion of 1/10 of the energy intake for a mixed diet with 10–15% of energy as protein, 20–40% fat, and the remainder carbohydrate, i.e., 10% of daily energy expenditure when intake meets expenditure. The activity-induced energy expenditure is the most variable component. The physical activity level of a subject is often expressed as an index: daily energy expenditure as a multiple of basal metabolic rate. The physical activity index ranges between 1.5 for a sedentary subject and 2.0 for an active subject. The absolute minimum is 1.0 for someone who does not eat or move. Values of the physical activity index over 2.5 can not be maintained without specific food supplements.

The reference for the physical activity index is doubly labeled water-assessed daily energy expenditure in combination with a measurement of basal metabolic rate. A typical observation interval for daily energy expenditure with doubly labeled water lasts one to three times the biological half-life of the label with the highest elimination rate, i.e., ^{18}O , resulting in ~7–14 days for a subject at high altitude. So far, five high altitude studies ([10](#), [11](#), [14–16](#)) included measurement of daily energy expenditure with doubly labeled water. In all five, basal metabolic rate was measured at a lower altitude, directly before the start of ascent or on return after descent.

The first study was on Mt. Everest ([14](#)). Subjects were two women and three men aged 36 ± 4 yr and with an average body mass index of 21.2 ± 2.2 kg/m², all members of an expedition to reach the summit. Two subjects were observed during preparation for the expedition, including a 4-day stay in a field laboratory on Mont Blanc in the French Alps (Observatoire Vallot, 4,260 m), with daily climbing activities between 3,500 and 4,800 m and subsequent 4-day time stays in a hypobaric chamber, simulating ascents to 5,600–7,000 m on Mt. Everest. All subjects were observed during the first summit attempt on

Mt. Everest, climbing between 5,300 and 8,872 m. Three subjects reached the summit (8,872 m) within 3 days after the observation interval, and in one subject the ascent to the summit was included in the observation interval. The physical activity index was 2.2 ± 0.3 , a value close to that of highly trained endurance athletes at sea level. Subsequent studies reported similar or even higher values of 2.8 ± 0.3 in three subjects climbing above 6,000 m (10) and 3.0 ± 0.7 in six subjects climbing between 5,300 m and the summit of Mt. Everest (11).

The observed level of daily energy expenditure in subjects climbing at high altitude is probably mainly caused by an increased activity-induced energy expenditure. However, an increased basal metabolic rate can not be excluded. Two studies calculated the physical activity index with basal metabolic rate values measured at sea level (10, 11). The third study used measured values at 5,050 m (14). In this study, subjects were adapted to high altitude for over 4 weeks and measured basal metabolic rate values were not systematically different from calculated values as determined with an equation based on subject characteristics and basal metabolic rate measured at sea level. Diet-induced energy expenditure was certainly lower than the standard 10% of daily energy expenditure mentioned above because subjects were in a negative energy balance (see below), leaving physical activity as the main determinant of the increase. Indeed, eight subjects staying for 21 days at the flat summit of Mt. Sajama (6,542 m), i.e., being mainly sedentary, had a physical activity index of 1.8 ± 0.3 (15). The value was measured over an interval of 10 days, 10 days after climbing to the summit. It was only slightly higher than the value of 1.5 mentioned above, which one would expect for a sedentary subject at sea level.

We calculated that the value of the physical activity index is close to the metabolic scope at altitude, i.e., the time-averaged metabolic rate that can be reached over periods long enough that metabolism is fueled by food intake rather than by transient depletion of energy reserves (14). VO_{2max} , the rate of oxygen usage under maximal aerobic metabolism, at altitude is ~50–60% of sea level. Thus the metabolic scope is decreased accordingly. At sea level, daily energy expenditure values of four to five times basal metabolic rate have been observed in Tour de France cyclists. However, at sea level subjects can maintain energy balance at four to five times basal metabolic rate. In the referred studies at altitude, subjects did not manage to meet energy expenditure with energy intake.

Energy intake

Energy intake at high altitude does not meet energy requirements, and subjects lose weight in the form of fat mass as well as fat-free mass. Energy intake measurements are usually based on self-report, with a tendency toward underreporting. Fortunately, altitude studies are closely supervised and subjects have to carry all of the food, a more optimal

situation in which to track intake. Subjects climbing Mt. Everest reported an energy intake of $\sim 55 \pm 10\%$ of measured energy expenditure (14). The discrepancy between intake and expenditure was related to weight loss. The mean energy equivalent of weight loss was 31 MJ/kg, within the range of 28–32 MJ/kg with 2/3 as fat and the remainder water and protein, as observed in weight loss studies at sea level. Thus the energy balance equation fitted. There was a tendency toward intake decrease during the observation interval while subjects were reaching higher altitudes.

In the study on subjects staying for 21 days at 6,542 m, energy intake over an interval of 10 days, 10 days after climbing to the summit was $76 \pm 14\%$ of measured energy expenditure (15). Here, body weight loss was 4.9 ± 2.1 kg over the 3 weeks and was equivalent to a cumulative discrepancy between intake and expenditure of ~ 150 MJ. The subjects did not attain energy balance despite a low level of physical activity and ad libitum access to food. However, the energy balance was not as negative as in the subjects climbing and going up to higher altitudes, referenced above.

Westerterp-Plantenga et al. (19) did a study to assess the contribution of long-term hypobaric hypoxia per se, without interference from cold and stress, to changes in different features of appetite that may explain the changes in size and composition of the diet at high altitudes. Eight men were exposed to a 31-day simulated stay at several altitudes up to the peak of Mt. Everest in a hypobaric chamber. Body mass reduction of 5 ± 2 kg was mainly due to a reduction in energy intake of 4.2 ± 2.0 MJ/d. Initially, meal size was reduced because of a more rapid increase of satiety during the meal. Part of the effect of reduced meal size on daily intake was compensated by an increase in meal frequency from 4 ± 1 to 7 ± 1 eating occasions per day. At 7,000 m and higher, AMS symptoms were present, resulting in uncoupling between hunger and the desire to eat; although subjects were hungry they had no desire to eat. The mechanism responsible for the decrease in energy intake is not yet clear. One explanation is a reduction of appetite through elevated serum leptin concentrations at high altitude (13). Leptin is a key mediator in the neuroendocrine regulation of food intake (5).

A clear solution for the altitude-associated decrease in energy intake does not yet exist. There have been suggestions that subjects at high altitude show a preference for carbohydrate. We did not see a difference in diet composition at high altitude versus reported values at sea level (14, 15, 17). Subjects consumed 46–54% of energy intake as carbohydrate, 13–17% as protein and 31–37% as fat. One study monitored the choice of food items with increasing altitude from 5,300 to 8,000 m and reported an increasing contribution of high fat and high carbohydrate foods to total energy intake as a function of increasing altitude (12). However, in a later publication of the same study it appeared that there was a significant underreporting of intake of on average 35% (11), and thus selective underreporting might bias reported intake.

One could offer carbohydrate-rich food in items that can be consumed in a nibbling pattern. The disadvantage of carbohydrate-rich foods is the lower energy density compared with fatty foods. Studies on energy balance at high altitude including energy-

dense food supplements, as are commonly eaten by professional endurance athletes, are not yet available.

▶ Water intake and water loss

Water requirement at high altitude theoretically increases due to increased insensible water loss at low ambient water vapor pressure. In practice, however, water loss at altitude is not higher than at sea level. We measured a water loss of 3.3 ± 0.6 l/d in subjects climbing Mt. Everest (14) and of 3.0 ± 0.5 l/d in sedentary subjects at 6,542 m (15). Water loss is very much a function of intake, and a subject drinks more when physically active, especially in a hot environment. In a comparative study on water balance at sea level and at 4,350 m, water loss decreased from ~4.5 to 3.5 l/d, mainly as a result of a decrease in ambient temperature of $\sim 10^\circ\text{C}$ (17). At high altitudes, subjects often experience an even higher reduction of ambient temperature.

One study compared water loss under identical environmental conditions with regard to temperature and relative humidity at two altitudes, 5,000–7,000 m and 7,000–8,848 m, in a hypobaric chamber (16). Total water loss showed a tendency to decrease from 3.7 ± 0.6 to 3.3 ± 0.8 l/d. Absolute insensible water loss was unchanged, at 1.67 ± 0.26 and 1.66 ± 0.37 l/d, respectively. Insensible water loss was closely related to daily energy expenditure and, adjusted for daily energy expenditure, was higher at the higher altitude. However, the increase in insensible water loss was counterbalanced by a decrease in metabolic rate that probably limited the increase in respiratory evaporative water loss.

Altitude exposure in the presence of sufficient food and water causes problems regarding how to increase water loss. Fluid retention at altitude is one of the causes of AMS (2). AMS is often followed by high altitude pulmonary edema (HAPE) and high altitude cerebral edema (HACE). The pathophysiologies of HAPE and HACE are complex and poorly understood (1). The measures to avoid AMS, HAPE, and HACE are slow ascent and descent to a lower altitude when symptoms manifest. The optimal altitude gain differs between individuals; some can go quickly, but others have to take great care at altitudes $>2,500$ m.

▶ Intestinal absorption

In a healthy person, the digestion of food is very effective. The digestibility is high because most of the food products eaten are refined. One of the few indigestible

components is dietary fiber. Only 4–7% of the energy ingested is lost in the feces. Early studies reported a decreased fat absorption at high altitude. Later studies did not confirm the findings and suggested that there might have been interference by gastrointestinal problems such as diarrhea (8).

Usually, food digestion is measured over an interval of at least 3 days. Total food and feces are collected over the observation interval, weighed, homogenized, and sampled. The beginning and end of the feces collection is indicated by a marker that subjects ingest before the first meal and after the last meal of the interval. Energy content of food and feces samples is measured by combustion in a bomb calorimeter.

In chronological order, Kayser et al. (8) observed a digestion efficiency of $96.2 \pm 2.0\%$ in subjects during a 1-month stay at 5,000 m. Westerterp et al. (15) measured $85.2 \pm 4.7\%$ in subjects staying at 6,542 m. Energy digestibility was $94 \pm 2.9\%$ at normoxia and $94.2 \pm 1.3\%$ at a simulated altitude of 7,000 m in a hypobaric chamber (16). In conclusion, in only one of three recent studies there was an indication of malabsorption at high altitude. It must also be remembered that the decrease of energy intake reduces the demand on the intestinal absorptive capacity.



Discussion

Humans do not seem to be able to maintain energy balance at high altitude. The critical altitude can not be defined exactly but starts between 5,000 and 6,000 m. Imbalance between energy intake and energy expenditure seems to be mainly due to a reduction in energy intake. The reduction in energy intake is caused by a change in the appetite profile and in the attitude toward eating. Initially, increased satiety during the course of a meal results in a reduction of meal size, which is partly compensated by an increase in meal frequency. The rapid increase of satiety during a meal is likely to be related to the hypoxic circumstances. A short-term increase in energy expenditure, namely diet-induced energy expenditure, emphasizes the relative lack of oxygen, resulting in decreased meal duration and thus in decreased energy intake (18). Acute mountain sickness at higher altitudes results in a further loss of appetite, although hunger is still present.

Malabsorption of ingested food does not contribute significantly to the negative energy balance at the observed low levels of energy intake at high altitude. It might become important when intake is increased to a higher level. Food supplements at high altitude should, on theoretical grounds, be rich in carbohydrates. Protein is the most satiating of the three macronutrients. Fat is the most likely candidate for malabsorption. Carbohydrate is thought to be the preferred fuel because of its higher yield of energy per mole of oxygen (9). The energy equivalent of oxygen is 18.7 kJ/l for protein, 19.6 kJ/l for fat, and 21.1 kJ/l for carbohydrate.

With regard to loss of body water, one of the problems of high altitude is the maintenance of water balance. Water availability is low when the only water source is melting snow. Theoretically, the water requirement is increased due to increased insensible water loss at low ambient water vapor. However, the increase in insensible water loss due to decreased barometric pressure is counterbalanced by a reduction of metabolic rate. The reduction in metabolic rate limits the increase in respiratory evaporative water loss. Additionally, cold weather clothing will curtail loss through the skin. A (initial) negative water balance may be an adaptive mechanism. Subjects showing negative water balance by an increased diuresis in the first days of altitude exposure show a great reduction in acute mountain sickness.

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