Optimizing Nutrition for Performance at Altitude: A Literature Review

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Abstract

Human beings are unique for their capacity to maximize their physical potential through various means. High altitude mountaineering is one such way that people challenge generally accepted notions about what is biologically and evolutionarily possible. While a 20,000+ft summit may be uninhabitable for extended periods of time, enterprising individuals have demonstrated that even the most remote locations are accessible with sufficient physical effort and proper strategy. High altitude athletes, and the scientists who study them, generally focus their research and preparation on physiological parameters, with a particular emphasis on the cardiopulmonary system. While careful scrutiny in this area is certainly justified, the relationship between physiological output at altitude and nutrition is somewhat neglected in the literature. Many athletes, alpinists included, consider eating to be instinctive and mundane. However, very few activities at 30,000ft or even 15,000ft are intuitive. Furthermore, nutrition is one of the few variables mountain athletes can control in an otherwise unpredictable environment. Despite the intrinsic limitations and seemingly contradictory findings often associated with performance nutrition studies at high altitude, mountain athletes should adhere to certain dietary guidelines related to macronutrient composition, micronutrient supplementation, and hydration status.

In addition to elite climbers, military personnel routinely operate at altitudes above 13,000ft. Consider the case of a search and rescue team responding to a downed helicopter in Afghanistan. The terrain in Afghanistan necessitates that aircraft fly above mountain passes up to 15,000ft in altitude in low light conditions and inclement weather. The recovery team must respond immediately (e.g., no time to acclimate) once alerted about a crash in order to secure the site and provide medical care. Not only must the recovery team deal with obstacles inherent in any mountaineering expedition (e.g., weather, falls, frostbite, loss of communication, etc), it also faces possible resistance from a hostile force. Operators with inadequate nutrition are ill-prepared to effectively overcome these threats to mission success and, in turn, reach their patients expeditiously to perform life saving interventions. When suboptimal nutrition is regarded as an impediment to mission completion, the importance of fueling one's body on the mountain becomes much more difficult to ignore.

Unfortunately, the studies performed at high altitude are often conducted under field conditions, where it is difficult to control for certain variables. The "cleaner" studies, in turn, may lack construct validity because they fail to account for the dynamic nature of high altitude mountaineering. In the field setting, subjects are typically reluctant to alter their routines making it difficult to test different nutritional protocols. Additionally, few nutritional researchers have the training or desire to study subjects at 15,000+ft. Furthermore, what elevation above sea level constitutes "high altitude" for the purpose of making nutritional generalizations?

Researchers in this area are still learning to ask the right questions. The search and rescue team conducting a 24 hour operation at altitude, for example, probably has different nutritional needs than a team of climbers attempting to summit Mount Everest. One area of interest is the relative contribution of different macronutrients on performance at altitude, the implication being that an ideal ratio might exist. Combating weight loss caused by increased metabolic activity and decreased appetite at altitude is another subject of critical inquiry among climbers and sports nutritionists. However, considering successful athletes in various sports have a particular somatotype, perhaps a certain degree of weight loss at extreme altitudes is not only inevitable, but adaptive. As with most aspects of sports nutrition, the literature investigating the relationship between nutrition and performance at altitude generates as many questions as it answers. Despite the seemingly conflicting data, certain measures can be taken by alpine athletes to mitigate potential performance impairments at altitude.

"Making Molehills Out of Mountains: Maintaining High Performance at Altitude" is a review that addresses both physiological and nutritional considerations associated with high altitude performance. The authors defined high altitude as elevations above 2600m or 8600ft. High altitude physiology affects performance in the following ways:[1]

1) Low O_2 → Tissue Hypoxia → ⬇ Work Capacity of Cardiac and Respiratory Systems
2) 3% ↓ in exercise capacity for every 300m above 1500m.
3) Poor sleep quality compounds the decreases in exercise performance and cognitive function caused by hypoxia

The nutritional recommendations the authors advocate to maximize performance at altitude focus on hydration, nutritional quantity, and nutritional composition. Fluid loss at altitude is attributed to increased sweating from exertion, ventilation changes occurring in cold, dry air, and cold weather diuresis. The latter condition is characterized by the increased urine output associated with shunting of blood to the core and the deceivingly high pressure readings in the baroreceptors as the body attempts to maintain normothermia. Based on available research, the authors recommend that athletes working at altitude consume 3-5L of fluid per day to replace losses from respiration, urine, sweat, and heat regulation.[1] The authors caution that consuming too much water may be counterproductive because it disrupts the decrease in plasma volume and increase in hemoconcentration that may be a positive adaptation upon one's initial exposure to altitude. However, this concern seems more theoretical than practical since most athletes tend to underconsume fluid on the mountain, especially when they must melt snow to hydrate themselves.

With regard to nutritional quantity, Freidlander et al., emphasize the importance of adequate caloric intake at altitude. Weight loss at altitude, a common phenomenon, is triggered by increased basal metabolic rate (BMR), increased exertion, appetite suppression associated with hypoxia, and limited food availability.[1] While caloric deficit does not seem to affect performance in the short term, it may negatively impact work capacity in expeditions lasting weeks or months. Additionally, appetite may not reflect nutritional needs at altitude. Since the relative contribution of carbohydrates as a fuel source may increase at altitude, adequate carbohydrate intake is emphasized by the authors. In the short term (three weeks or less), caloric deficit may not impair performance as long as glycogen stores are maintained.[1] Consequently, the authors recommend that 60% or more of a mountain athlete's caloric intake come from carbohydrates as a means of ensuring adequate glycogen storage. While research on the effect of fat intake at altitude is limited, the authors regard high fat foods as valuable to alpine athletes because they tend to be calorically dense and easy to transport in the field. While Freidlander's guidelines for high altitude nutrition are generally conservative and uncontroversial, their carbohydrate recommendations are higher than what is supported in the literature.

Benso et al., assessed the metabolic and endocrine adaptations in nine male, well-trained, elite climbers from the 2004 Italian Mount Everest expedition team, five of whom reached the summit (8852m). The remaining four all climbed to at least 7500m. While the authors did not focus explicitly on nutritional interactions, their findings have nutritional implications. The climbing team completed a progressive acclimatization program prior to arriving at Mount Everest base camp and commencing the study. The subjects completed a metabolic and hormonal evaluation (following an overnight fast) one month before the expedition and at base camp upon returning from their summit attempt. While there is no mention of absolute caloric intake, the climbers had access to palatable foods and on average consumed a diet that contained 58% carbohydrate, 30% lipid, and 12% protein. The results were as follows: no Acute Mountain Sickness or edema, average weight loss of 5kg, ↑ growth hormone-insulin-like growth factor (GH/IGF-1), ↓T_3, no change in leptin or ghrelin despite body weight loss, ↑ prolactin and progesterone, ↓ testosterone, no change in cortisol, ↑ dependence on glucose, ↑ insulin sensitivity, and ↓ relative contribution from lipid.[2] The authors speculate that these changes may have been caused by low tissue oxygen, dehydration, and/or nutritional interactions. Since exercise is known to enhance GH response to GH-releasing factor, it is uncertain whether the GH increases were caused by exercise, altitude, or a combination of both; none of the subjects remained at base camp during the study so it is not possible to differentiate. The authors speculate that the upregulation of the GH/IGF-1 axis may trigger protein anabolism while influencing changes in carbohydrate and lipid metabolism.

They also speculate that prolactin may affect glucose metabolism.[2] Furthermore, they suggest the increase in prolactin may reflect stress induced changes in testosterone production. This suggestion is contradicted, they concede, by the lack of change in cortisol or adrenocorticotropic hormone (ACTH). The mechanism by which leptin and ghrelin remained the same despite the significant decrease in body weight requires further study. The results do, however, support the notion that satiety signals that suffice at sea level may be altered at high altitude, which reaffirms the notion that mountain athletes should not rely on hunger as an indicator of nutritional status. The authors deserve praise for collecting data under such severe conditions on world class athletes. Their findings help generate the following questions for future research:

1) Would the metabolic and hormonal profiles of these athletes vary if caloric intake was controlled (e.g., less of an energy deficit)?
2) Do these metabolic changes occur at lesser (albeit still "high") altitudes or are they specific to the tallest mountains in the world, like Mount Everest?
3) Is the increased dependence on glucose seen in these athletes a product of the relatively high exercise intensity they are able to maintain at altitude? Do well-trained, but not world-class climbers exhibit different substrate utilization while traveling at lower speeds and with less intensity?
4) In light of the possible influence of prolactin and progesterone on glucose metabolism, do females and males each have different nutritional needs at high altitude?

In another Mount Everest study, Reynolds et al., employed a double crossover design over nine weeks to determine the effects of variable macronutrient distribution at high altitude on five women and ten men from the United States, Mexico, and The Netherlands. The ten most experienced climbers attempted to summit while the other subjects never exceeded 5600m in altitude and remained primarily at base camp. All of the subjects followed a strict acclimatization protocol prior to arriving at base camp. The researchers divided the subjects

into a high fat, low carbohydrate group (35 and 50%, respectively), *A*, and low fat, high carbohydrate group (20 and 65%, respectively), *B*. The randomized crossover design protocol was as follows:

Weeks 1-3: Assigned Diet
Weeks 4-6: Alternate/Non-Assigned Diet
Weeks 7-9: Original, Assigned Diet

At base camp, climbers were given prepared meals based on previously stated food preferences. Foods were self-selected during the actual expedition due to logistical constraints not encountered at base camp. However, Diet A contained 49 items not permitted on Diet B, including tuna and sardines in oil, various cheeses, shredded coconut, margarine, and other high fat foods. All subjects kept daily food logs regardless of altitude attained. All but one subject lost weight. The authors did not consider the degree of overall weight loss excessive considering the extreme altitude. While the mean caloric intake for the climbers was significantly greater than that of the people who remained at base camp (2841 vs. 2442), there was an appreciable reduction in energy intake at progressively higher altitudes. The climbers did not alter their relative macronutrient contributions as they traveled further from base camp challenging the pervasive notion in the climbing community that carbohydrates are the preferred fuel at higher altitudes. This idea, the authors contend, is driven more so by anecdotal stories (one of which is an anonymous study from 1938) than actual research.

In fact, while the authors intended for the subjects from Groups A and B to have discrete relative dietary fat intakes, there was no significant difference in mean percent fat intake for either group.[3] The subjects appeared to self-select diets that provided 28% energy from fat and there was an apparent regression towards the mean carbohydrate and fat intake. That the subjects' preference for fat was higher than expected is encouraging when one considers that fatty foods occupy less space in a climbers pack than less calorically dense foods. Despite these trends, there was considerable variation in caloric intake among the subjects regardless of altitude reached. While formulas and algorithms for energy demands at altitude may be used as a guide, an individual approach is clearly needed.

The authors acknowledge that it is not feasible to discern the individual impact of the numerous stressors (e.g., cold, increased exertion, threats to survival, separation from family, etc) in a study of this nature. They follow that caution, however, by criticizing more rigid studies in hypobaric chambers that control for confounding factors: "Thus it is necessary to utilize actual mountainous conditions to discern the full impact on human performance".[3] There are advantages and disadvantages to both field and laboratory research at altitude making it especially hard to generate concrete recommendations. Due to the difficultly of finding subjects capable of "performing" under such arduous conditions, this study is limited by its small sample size. Another inherent limitation of field nutrition studies like this one is that data collection is contingent on accurate reporting from the subjects. The precision of such reporting may be compromised not only by impairments in cognitive function that occur at altitude but also by climbers' preoccupation with more pressing issues (e.g., survival!).

Another study by Reynolds et al., (different coauthors, 1999) examined the regional changes in body composition and net energy balance at high altitude (5300-8848m). Energy expenditure was assessed with doubly labeled water, a method that calculates carbon dioxide production and oxygen consumption from the excretion of different water isotopes and dietary records, respectively.[4] Three base camp personnel and seven climbers received doubly labeled water to determine energy expenditure on Mount Everest. The researchers were unable to control for variables like age and gender because assignment to the climbing team was dependent on previous mountaineering experience. Consequently, there was an overrepresentation of males in the climbing group and of females in the base camp group. Two months prior to leaving the United States, all subjects had their resting energy expenditure calculated by indirect room calorimetry. However, energy expenditure on the mountain was determined with doubly labeled water, which was a methodological limitation, albeit one justified under the circumstances. Body composition in the field was assessed with the skinfold method and there was no direct measure of the subjects' hydration status. All subjects were required to keep a detailed food log throughout the nine weeks. Body weight loss, not percent muscle mass or percent fat lost, was greater for the climbing group. Neither group lost a significant percentage of body fat relative to baseline measurements. Mean energy intake (2928 vs. 2149kCal) and percent increase in energy expenditure (298 vs. 243%) were considerably higher for the climbing group.[5]

The authors observed that the expected body weight loss did not correlate significantly with actual losses, a discrepancy they attribute to underreporting of kCals. As previously mentioned, food log accuracy is often questionable in field research of this nature. Nevertheless, in light of the various metabolic and hormonal changes that occur at altitude, a "calories in-calories burned" model seems an insufficient and overly simplistic means of predicting weight loss on Mount Everest. The authors also suggest that rapid bodyweight loss, fluid shifts, and dehydration at altitude may reduce the validity of skinfold measurement. Furthermore, skinfold measurement often fails to detect the subtle changes in body fat percentage that may occur at altitude. Nevertheless, they conclude that there may be a preferential loss of body fat reserves and sparing of muscle tissue at altitude.[5] This issue remains controversial in high altitude nutrition studies partially due to the lack of protocol standardization. Reynolds et al., propose that a certain amount of weight loss may be inevitable since it is so difficult to maintain adequate caloric intake at extreme altitudes. Consumption of high fat, calorically dense foods may, however, help minimize the degree of weight loss.[5]

The inability to isolate the effects of all the variables that may affect performance at altitude is a limitation of field nutritional research, like that conducted on Mount

Everest. Mount Everest is the absolute furthest thing from a controlled environment. It is often assumed that hypoxia triggers the physiological changes that occur at altitude. Rose et al. monitored six trained, young male subjects for 40 days in a hypobaric chamber to determine if hypoxia per se results in weight loss and changes in dietary preferences. The idea was to artificially replicate an expedition on Mount Everest, with the subjects "summiting" at a simulated altitude of 8,848m. The subjects were provided with three meals a day; the composition of which was 60% carbohydrate, 25% fat, and 15% protein. However, the subjects only consumed foods for which they had a taste. They also had access to various exercise devices in the chamber. Energy expenditure was calculated using a modified Harris Benedict formula. At the end of the 40 days, mean caloric intake decreased 43% and mean weight loss was 8.9%.[6] Unlike the Reynolds body composition study conducted on Mount Everest, there was no preferential retention of muscle mass; lean tissue accounted for 67% of the weight lost. The subjects lost more weight than the researchers expected based on the energy expenditure estimates. Predicting weight loss from formulas and simplistic models may be difficult as was alluded to previously.

Carbohydrate intake decreased from 62.1% to 53.2% by the end of the study.[6] The decrease in relative carbohydrate intake led the researchers to conclude that the apparent carbohydrate preference championed by many climbers is likely attributable to the convenience and accessibility of these foods, not to a physiological phenomenon. Since temperature and humidity were maintained at a comfortable level, it seems that hypoxia per se was responsible for the observed weight loss. Furthermore, while the subjects were encouraged to exercise, their activity levels were not comparable to those required on an actual expedition. While weight loss may have been influenced by malabsorbtion of macronutrients at increasing altitudes, this study was not designed to explicitly test for this phenomenon. The model (hypobaric hypoxia) created by the researchers more closely simulates the atmospheric composition at altitude than that marketed by manufacturers of various commercially available altitude simulators. These devices induce hypoxia by lowering the percentage of oxygen without decreasing the overall barometric pressure. Consequently, they may not induce the same favorable adaptations for athletes preparing for challenging expeditions. This study clearly exercises an appreciably greater degree of control over confounding variables than the research discussed previously. However, these other variables may, in fact, have nutritional implications that warrant additional research using a more integrated approach.

While most research investigating the relationship between nutrition and performance at altitude focuses on macronutrient composition, some studies have focused on micronutrient interactions. The need for varying amounts of micronutrients at high altitude remains controversial, as it does in other areas of sports nutrition. It is theorized that antioxidant requirements may increase at altitude due to increased exertion and changes in oxidative metabolism. Simon-Schnass, in her review "Nutrition at High Altitude", suggests that prophylactic vitamin E supplementation may combat free radical damage associated with increased oxidative metabolism from exertion at altitude. Since vitamin E combats free radical damage during various steps in the aerobic pathway, a vitamin E deficiency, she maintains, may promote decreased cellular respiration and energy production; possibly contributing to the reduction in anaerobic threshold at altitude. Such negative physiological changes may be compounded by low partial pressure of oxygen and decreased exercise intensities with the same perceived exertions[7].

In one vitamin E study conducted at altitude, there was no change in pentane exhalation with vitamin E supplementation compared to a > 100% increase in the control group at 5100m; pentane exhalation is indicative of vitamin E status and lipid perioxidation.[7] Assuming pentane exhalation does indeed reflect lipid perioxidation, at what point do increases in lipid perioxidation negatively impact performance or health? Simon-Schnass also proposes that vitamin E supplementation protects against alterations in red blood cell filterability and increases in blood viscosity caused by perioxidation of membrane lipids.[7] Protein C, a coagulation inhibitor, is thought to indicate the extent of vascular wall changes induced by oxidative damage. Simon-Schass suggests that decreases in Protein C promote increased coagulation, which, in turn, triggers protease release (to deal with the coagulation) and subsequent damage to proteins in endothelial cells. This hemodynamic cascade may increase the risk of frostbite, retinal hemorrhage, and pulmonary and cerebral edema; all of which are potentially debilitating on the mountain. Some of the literature suggests that vitamin E supplementation prevents the decreases in Protein C observed at altitude. Vitamin E, therefore, may stabilize endothelial cells and prevent protein degradation in the vasculature.[7] While the results of vitamin E supplementation are promising, additional research that controls for caloric intake and baseline nutritional status is needed to determine: 1) The point at which decreases in Protein C are pathological at altitude and 2) How long one can continue to perform at altitude with amplified lipid perioxidation before the changes become consequential.

The literature investigating the effects of different hydration strategies at high altitude is also quite scarce. Richardson et al. assessed the degree to which euhydration, hypohydration, and hyperhydration during actute normobaric hypoxic conditions trigger Acute Mountain Sickness (AMS) symptoms and alter various physiological markers. The symptoms of AMS (nausea/vomiting, headache, dizziness, fatigue), while not suggestive of performance per se, should be avoided to optimize physiological output.[8] Increased water vapor loss, energy expenditure, and ventilation at altitude promote dehydration. At sea level, dehydration is associated with decreased oxygen delivery, heat dissipation, and cognitive function.[7] Overhydration, despite its positive effects on stroke volume, vasodilation, and heat dissipation at sea level, may worsen intracranial pressure and headaches at altitude via increases in extracellular volume.

For this study, eight physically active males, none of whom had spent time above 2000m in the previous two

months, completed intermittent walking tests at 50% VO_2 max after controlled euhydration, hyperhydration, and hypohydration in a normobaric hypoxic state with a seven day washout period between tests.[8] Hydration status was characterized by the degree to which subjects were permitted to replenish lost fluids following a moderate running session conducted fifteen hours prior to the actual test. The hypo- and hyperhydration states induced greater physiological strain and AMS related symptoms.[8] Although the authors were unable to identify the mechanism, the AMS symptom scores suggest that the hypo and hyperhydration states adversely affect feeling state, especially headaches, compared with euhydration.[8]

Based on the 0.6L/h sweat rate observed in the euhydrated state, Richardson et al., recommend that people consume up to 5L of fluid spread throughout the day in acute hypoxic environments. Moreover, because increased physiological strain may exacerbate AMS symptoms, a hydration state within normal physiological limits is optimal;[7] urine color at ~2, urine specific gravity < 1.015, and urine osmolality < 400 mosm/kg should be maintained during acute hypoxic exposure. While these recommendations seem reasonable, the following methodological limitations necessitate the need for additional research in this area:

1) Extremely fit individuals, like elite climbers and military Special Operations Forces, may react differently to various hydration states than did the subjects in this study, whose mean $V0_2$ max was 43ml/kg min. Are these results also typical of people, like many alpinists, who do take the time to acclimatize prior to exposing themselves to more extreme altitudes?
2) The observed effects of different hydration states may vary with greater exercise intensity and duration.
3) The study was conducted under normobaric conditions. Exposure to a lower percentage of oxygen at sea level may produce different physiological adaptations and responses than the hypobaric hypoxia encountered on the mountain. Environmental obstacles, like extreme cold, and increased stress may also confound the results.

These critiques not withstanding, the authors' emphasis on euhydration has important implications for rescue personnel and climbers treating AMS-related symptoms, namely that overhydration, in the form of large intravenous fluid boluses advocated by some medical protocols, is not necessarily the best way to reverse the extreme dehydration often encountered on the mountain. Consequently, developing a field expedient method of assessing hydration status may help optimize performance at altitude.

Based on the available literature, military personnel operating at altitude should focus on the following nutritional areas: maximizing caloric intake, adequate hydration, glycogen retention, and antioxidant support. Macronutrient percentage recommendations are generally impractical for climbers, especially those lacking the medical supervision commonly accessible on high profile expeditions like Mount Everest. Many of the altitudinal nutrition studies are conducted on Mount Everest because its base camp is able to accommodate so many physicians and researchers. Teams on Mount Everest typically more easily obtain funding for their research projects. While most climbers do not expose themselves to the extreme conditions that characterize places like Mount Everest, they too are limited by logistical and practical constraints; often more so because they do not have access to a resupply network. Furthermore, blanket macronutrient percentage recommendations are useless if they conflict with an athlete's individual preferences at altitude.

Consequently, adequate preparation is crucial. Operators should conduct numerous training sessions at less daunting altitudes to determine what foods they can tolerate. Since insufficient energy intake is so pervasive at altitude, simply consuming more calories may be a more reasonable goal for mountain teams and small units than trying to ascertain an appropriate ratio of carbohydrates, fats, and protein. However, as many authors emphasize, athletes should experiment with high fat, energy dense foods because these food sources may help Operators maintain a more neutral energy balance. While the degree to which weight loss at altitude impairs performance is still uncertain, Operators should seek to avoid drastic bodyweight changes. Adequate caloric intake is probably less important for units conducting shorter patrols (<48 hours, like the search and rescue team example from the introduction), but even these personnel should travel with energy dense snacks and a premixed liquid carbohydrate solution if possible. Once again, these teams should conduct training evolutions at altitude to determine how little food they need for sustenance on these shorter, albeit often more intense, outings. Regardless of the duration of exposure to altitude, the food Operators do bring to the field must be lightweight, easy to prepare, and palatable.

Like all endurance athletes, military Operators should seek to maximize glycogen storage during missions at altitude, especially since glycogen retention may be compromised by negative energy balance; this is a difficult fate to avoid during strenuous expeditions. While some researchers have recommended 1000-1200g carbohydrates/day for ultra endurance athletes, military personnel are unlikely to carry this amount of food. It's a vicious cycle: adding weight to one's pack, increased energy expenditure, greater need for food, etc. Nevertheless, a daily carbohydrate intake of around 600g, as advocated by some authors,[9] seems realistic. Mountain athletes who commence operations from base camps or military installations typically leave their staging area with 2-4L of fluid to avoid having to melt snow during the expedition. Such personnel should premix their water with a carbohydrate, electrolyte solution since they are unlikely to carry powders in the field. Additionally, they should ensure that they are adequately hydrated prior to breaking camp. The use of a prefilled "camel back" or water bottle while moving is essential. Since measuring specific gravity is generally not feasible in the field, urine color seems to be the most practical means of assessing hydration status at the moment.

Vitamin supplementation at altitude remains somewhat controversial. However, in light of the promising vitamin E research in this area, Operators should, at a minimum, ensure that they are not deficient in any micronutrients, especially vitamin E, prior to commencing physically demanding expeditions. Supplementing with 200mg of Vitamin E twice daily while on the mountain may help minimize oxidative damage even in alpinists with no preexisting deficiency.[7] Although optimizing nutrition for performance at altitude remains as much an art at this point as a science, units deployed to high altitude locations must be as thorough about nutritional strategy as they are about equipment selection, physiological training, and tactical preparation.

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