Energy at High Altitude

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Abstract

For the military doctor, an understanding of the metabolic effects of high altitude (HA) exposure is highly relevant. This review examines the acute metabolic challenge and subsequent changes in nutritional homeostasis that occur when troops deploy rapidly to HA. Key factors that impact on metabolism include the hypoxic-hypobaric environment, physical exercise and diet. Expected metabolic changes include augmentation of basal metabolic rate (BMR), decreased availability of oxygen in peripheral metabolic tissues, reduction in VO_2 max, increased glucose dependency and lactate accumulation during exercise. The metabolic demands of exercise at HA are crucial. Equivalent activity requires greater effort and more energy than it does at sea level. Soldiers working at HA show high energy expenditure and this may exceed energy intake significantly. Energy intake at HA is affected adversely by reduced availability, reduced appetite and changes in endocrine parameters. Energy imbalance and loss of body water result in weight loss, which is extremely common at HA. Loss of fat predominates over loss of fat-free mass. This state resembles starvation and the preferential primary fuel source shifts from carbohydrate towards fat, reducing performance efficiency. However, these adverse effects can be mitigated by increasing energy intake in association with a high carbohydrate ration. Commanders must ensure that individuals are motivated, educated, strongly encouraged and empowered to meet their energy needs in order to maximise mission-effectiveness.

Introduction

The operational effectiveness of troops deployed to a high altitude (HA) theatre depends in part on the critical ability to meet the mission-specific metabolic challenge. Individual success in achieving this depends upon a variety of factors (Table 1). It is widely accepted that a slow rate of ascent to high altitude facilitates effective acclimatisation and reduces the risk of acute mountain sickness and other complications [2]. In a military environment troops may be deployed rapidly and at short notice creating greater physiological demands including those of nutrition. An understanding of the metabolic effects of HA exposure is highly relevant to the military doctor.

HA is generally considered to represent a terrestrial elevation greater than 3,050m above sea level, although more specific definitions are given in Table 2. Exposure to HA frequently results in a reduction in body mass (in the region of 5 kg over a typical civilian expedition) secondary to losses in both fat mass and, to a lesser extent, fat-free mass [3]. This review examines the acute metabolic challenge and subsequent changes in nutritional homeostasis that occur in this unique and extreme environment. It will explore also the potential impact on physical wellbeing and individual mission-effectiveness. The metabolic effects of extremes of temperature merit consideration in their own right and are not discussed specifically here. Neither are those of prolonged residence at HA, which leads to adaptations beyond the scope of this article.

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- Hypoxia and hypobaria
- Physical exercise
- Water & Nutrition (Energy, Vitamins and Minerals)
- Heat & Cold
- Sleep & Affect

Table 1. Factors influencing the metabolic challenge at high altitude. Adapted from [1].

Terminology	Definition
Intermediate altitude	1500-2500m [1] e.g. Val Thorens – highest Alpine ski resort (2300 m)
High altitude	2500-3500m [1]
Very high altitude	3500-5800m [1] e.g.Mont Blanc (4810 m)
Extreme altitude	>5800m [1] e.g. Mount Everest (8848 m), Mount Kilimanjaro (5895 m)
BMR	Basal metabolic rate (minimum metabolic activity after waking and before getting out of bed)
VO_2 max	Maximum rate of oxygen uptake (usually expressed in litres min^{-1})

Table 2. Key definitions relating to metabolism and high altitude.

Acute metabolic demands and responses at HA

HA is a recognised stimulus to the sympathoadrenal system and exposure results in an increased secretion of norepinephrine within the first three weeks [4-7].These effects may be responsible for some of the metabolic changes seen at HA, such as augmentation of the basal metabolic rate (BMR) and lactate accumulation during exercise [1]. It has been found that, when energy intake is not allowed to fall below sea-level values, acute HA exposure elevates BMR by 30%. After three weeks exposure to HA, BMR is still 17% greater than at sea-level [8].

The fall in barometric pressure that occurs at HA results in a reduced partial pressure of oxygen in the atmosphere. 'Hypobaric hypoxia' is unfavourable to oxyhaemoglobin dissociation and impairs the oxygen unloading that occurs in metabolically active tissue. This effect is compounded by the cardiovascular response to HA with shunting of blood away from the periphery towards the heart, lungs and brain [1].

Glucose is the most efficient fuel that the body can utilise, consuming less oxygen per unit of energy produced than either fat or protein. This is of particular relevance in hypoxic situations, such as those at HA. Exposure to HA results in a lower blood glucose in the first 40 hours [9], suggesting enhanced glucose utilisation and, when energy balance is maintained through adequate carbohydrate intake, glucose dependency increases at rest [10]. These findings are congruent with the increase in insulin sensitivity that is known to occur at HA. Furthermore, it has been postulated that hypoxaemia may enhance muscle uptake of glucose by other mechanisms that are yet to be fully elucidated [11,12].

Acute metabolic demands and responses during exercise at HA

While metabolic demands at rest are important, the metabolic demands of exercise at HA are crucial. Activity at HA requires more energy than it does at sea level. Using doubly labelled water (DLW), it has been found that the total energy requirement in individuals active at HA is 2.2 to 2.3 times the resting sea level requirement, whereas the energy requirement for equivalent activity at sea level is as low as 1.5 to 1.8 times resting [13]. During field training at 2,500 to 3,100m elevation, daily energy expenditure in Special Forces soldiers has been determined by DLW to be 3.0 to 3.4 times resting (4,558 +/-566kcal day^{-1}) [14]. It is recognised also that any given exercise task at altitude will be accomplished at a relatively greater effort (exercise intensity) than at sea level. This increase in effort is partly explained by the decline in VO_2 max with HA. VO_2 max decreases by approximately 10% for every 1,000m increase in altitude above 2,000m [15-17]. Conversely, oxygen consumption is constant for any given power output of sub-maximal exercise, independent of the altitude – so equivalent work may require a greater proportion of available maximal effort as altitude increases and VO_2 max falls. Even slow ambulation can become a high intensity activity, with commensurate metabolic demands, at HA.

At sea level, exercise intensities above 50% of VO_2 max will result in the utilisation of less lipid and more carbohydrate during exercise [18]. Exercise during acute exposure to HA also results in a shift in substrate metabolism. Glucose is the most oxygen efficient fuel and a shift away from reliance upon free fatty acid (FFA) consumption, towards increased glucose dependence, could conceivably be advantageous in an environment where oxygen transport and utilisation are limited. On acute HA exposure, the rate of glucose uptake by exercising skeletal muscle has been shown to increase relative to sea level, in parallel with a fall in uptake of FFAs. This suggests that exercising at HA increases muscle utilisation of glucose as a substrate, and decreases emphasis on fat metabolism, in an attempt to improve muscle efficiency [19].

An acute hypoxic insult, such as exposure to HA, causes exaggerated blood and muscle lactate concentrations during submaximal exercise [20]. It is thought that these differences, too, might reflect increased glycolysis [7]. It has been suggested that changes in glycolytic flux rate may occur as a result of changing availability of glucose-6-phosphate (the substrate), or by changes in the glycolytic pathway at an enzymatic rate-limiting step. Increased glycolysis might represent a metabolic adjustment in order to protect oxidative phosphorylation as the primary mechanism of maintaining ATP concentration in the working muscle during acute HA exposure [21].

Although epinephrine has been shown to alter muscle glycogenolysis during exercise [22], β-adrenergic input does not appear essential to increased dependence on glucose during exercise at altitude, if dietary intake matches energy need [23]. The extra- and intracellular signals for the altered patterns of lipid and glucose metabolism described above are yet to be elucidated satisfactorily [7, 23,24].

Mission reality: acute metabolic demands and responses in the energy deficient state during military and civilian exposure to HA

It has been reported that soldiers participating in field exercises in mountainous terrain have consistently high rates of daily energy expenditure, but limited dietary energy intake [14]. In the absence of regularly scheduled hot rations, soldiers (at sea-level) do not consume enough food to meet the energy requirements of strenuous field taskings [25]. Factors determining ingestion of military rations include palatability, weight of rations and load carriage considerations, concurrent illness (especially diarrhoea and vomiting), altitude and environmental temperature, intervention of commanders and the tempo of operations or exercise. It is speculated that anorexia may be an innate adaptive mechanism, acting to limit post-prandial impairments in attention and reaction speed [26,27].

In order to prevent changes in body mass, energy balance must be neutral (i.e. energy intake equals energy expenditure). Partly as a result of this increased energy expenditure at HA weight loss, though not inevitable, is exceedingly common [8, 28-31]. The daily energy expenditure climbing Mt. Everest has been variably reported as 3250 kcal day^{-1} [16] but also up to 5394 kcal day^{-1} and in some individuals' 7871 kcal day^{-1} [32], a massive increase over sea-level expenditure. Energy expenditure depends on a combination of factors including food intake (diet-induced thermogenesis), body size (which influences BMR) and level of physical activity. As such the weight loss that occurs at HA is multi-factorial (Table 3).

Loss of appetite is a near universal consequence of rapid ascent to HA and has a significant effect on the ability to maintain energy balance. Anorexia is possibly mediated by hypothalamic mechanisms but gastrointestinal signals causing nausea as part of the syndrome of Acute Mountain Sickness (AMS) are a common exacerbating factor. Indeed, nausea is an important feature of AMS which itself is common, occurring in up to 60% in those

- Reduced food intake due to
  - loss of appetite (causes include Acute Mountain Sickness and gut discomfort due to decreased barometric pressure)
  - unpalatable food
  - inadequate supply
- Changes in endocrine parameters controlling homeostasis
- Imbalance of energy intake and expenditure, due to
  - increased basal metabolic rate
  - high activity levels that are not matched by food intake
- Reduced body water due to
  - insensible losses (increased ventilation)
  - diuresis
  - reduced water intake
- Disease, including altitude-specific illnesses
- Genetic and cultural factors, including climbers 'bulking-up' pre-expedition/deployment

Table 3. Factors contributing to weight change at HA. Adapted from [1].

ascending to around 4500 metres [32]. If unchallenged, anorexia will result in less food being eaten than at sea-level. The effect of acute exposure to moderate HA on energy balance is also typically negative, with food intake reduced by as much as 25 to 50% [28, 33-36]. A sustained reduction in energy intake, as noted in starvation, reduces appetite further. One physiological effect of hypobaric hypoxia, as described above, is the increase in BMR and this further exacerbates the problem by increasing the energy requirement of personnel at HA. The energy gap at HA (compared to sea-level) has been calculated as approximately 480 kcal day^{-1} (300 kcal day^{-1} due to raised BMR [8], reduced food intake of 180 kcal day^{-1}) [31, 37-38] and this equates to a weekly weight loss of 0.5kg fat. These figures will depend on the expedition duration, rate and conditions of ascent, final altitude achieved and type of fuel being oxidised. The effects of higher physiological energy demand can be mitigated by reducing physical demands, but military personnel operating at HA are unlikely to be sedentary and high activity levels will further add to the already increased energy need. Even greater energy intake is required in order to remain energy neutral. Failure to bridge the gap between inadequate energy intake and increased energy requirements results in loss of body mass. The metabolic similarities to starvation have been widely documented – the preferential primary fuel source shifts from carbohydrate towards fat; diuresis occurs and nitrogen balance becomes negative.

The effects of exercising combined with acute exposure to HA on weight and lean body mass can be profound. The degree of weight loss may be related to the altitude achieved. In support of this, a direct relationship between severity of hypoxia and body mass loss has been demonstrated in animals [39], but not decisively proven in humans. Early studies, though aiming to improve food intake, resulted in even less energy consumption [40,41]. Unpalatable diets may have been responsible. Even when quality 'desired' food was provided, food intake decreased over time [37,42]. The majority of studies investigating energy intake have found that people feeding *ad libitum* at HA would invariably consume quantities of food inadequate to balance their energy expenditure [37]. However, some evidence suggests that body mass and body composition can be maintained at HA in both active and sedentary populations if they are highly motivated, educated, strongly encouraged and empowered to meet their energy needs [8,23]. In contrast to this, more recent work has shown weight loss can occur despite adequate carbohydrate supplementation [43]. There is no convincing evidence that intestinal malabsorption plays a role in negative energy balance observed at HA [44].

Alterations in body composition are difficult to measure at HA. Indirect measures such as skinfold thickness and muscle girths may be affected by peripheral oedema. Likewise, alterations in fluid balance at HA limit the applicability of other methods (such as isotope dilution or bioimpedance analysis) which rely on the assumption that the hydration of the body's fat-free mass is constant. Nonetheless, studies have concluded that the majority of body mass loss is due to loss of fat mass. Although muscle mass may be lost too, it is preserved relative to fat mass [30,37,43,45]. Exercise appears to be important for protein utilisation at HA. Acute moderate hypoxia has been linked to altered protein metabolism, with increased albumin degradation occurring during the first three days at 4,300m [36]. A negative nitrogen balance may occur at HA if energy balance is not maintained. However, there is evidence that a normal nitrogen balance can be sustained, even in the face of a moderate negative energy balance (-200kcal day^{-1}) [46]. It has been suggested, in fact, that training may have a protective effect on protein utilisation [46] and this effect may operate at HA in spite of contrary influences related to hypobaric hypoxia.

Although energy expenditure at rest has been shown to decline to near sea level after two to three weeks habituation to HA, [47,48], this may be due to loss of metabolically active tissue [24], over and above other physiological or metabolic adaptations. In the absence of adequate dietary carbohydrate intake, glycogen synthesis is impaired and the body's carbohydrate stores are readily depleted [49]. U.S. military personnel have been shown to achieve a field carbohydrate intake of around 300 g per soldier per day [14,50], which falls well short of the 400 g (minimum) recommended [51]. In such circumstances, a switch to fat-predominant fuel metabolism occurs with its attendant oxygen cost and reduction in muscle efficiency. The body's fat energy reserve, which is approximately 98% of the total body energy reserve, can meet a 2,000 kcal energy deficit for over a month in a typical young male soldier [49]. However, decreased physical performance [52,53] and loss of lean body mass [54] characterise this state.

Metabolic 'so-whats' for troops rapidly deploying to HA

In military personnel at HA, maintenance of body mass is considered imperative, in order to limit decline in physical and mental capability [55,56]. However, not all studies conclude that weight loss adversely affects performance [57] and it may be that, in the short-term, anorexia, diuresis and weight loss are adaptive responses to limit AMS. Ultimately, however, sustained weight loss is likely to be detrimental.

Individuals in negative energy balance respond differently to HA, compared to those forced to consume energy sufficient to cover needs. Maintenance of adequate intake has been associated with the avoidance of body mass losses attributable to water, fat loss and muscle wasting [58]. Furthermore, troops training above sea level have demonstrated preservation of both lean body mass and performance parameters when encouraged to increase energy intake, in association with provision of a special high-carbohydrate military ration, even though energy balance remained negative [59].

Adequate feeding may, however, increase overall energy needs at HA. Basal energy needs remain elevated in the adequately fed individual at HA, perhaps in consequence of maintained body mass and composition in the face of increased metabolic demands. In a state of neutral or positive energy balance, increased emphasis on glucose as the 'fuel of choice' may proceed in parallel with decreased FFA consumption both at rest and during exercise [10]. Adequate feeding also reduces the HA diuresis [38], although appropriate diuresis is a necessary component of physiological adaptation to acute HA [60,61].

The macronutrient requirements of military personnel and climbers at HA have been extensively investigated. In terms of macronutrient provision, some evidence suggests that a preference for meals high in carbohydrate occurs at HA [37] while another study showed climbers preferentially chose high-fat diets [62]. Fat is the most energy dense macronutrient (an important consideration in the development of ration packs), but yields less energy per unit oxygen consumed when compared to carbohydrate (4.69 kcal l^{-1} vs. 5.05 kcal l^{-1}) a highly relevant fact in the oxygen-poor environment of HA [63]. High carbohydrate diets that facilitate carbohydrate as muscle fuel will thus require less oxygen per unit of substrate utilized and will also move the respiratory quotient to the right; from 0.7 (pure fat) towards 1.0 (pure carbohydrate). This has a theoretical benefit at HA - a higher alveolar pressure of oxygen (PAO_2) is created for any given alveolar pressure of carbon dioxide ($PACO_2$). At altitude, $PACO_2$ is reduced and thus a higher PAO_2 will be observed with a high carbohydrate diet compared to a high fat diet. It has been shown that a carbohydrate-rich diet does indeed improve levels of hypoxaemia at HA [64,65]. Crucially, studies investigating the effects of high carbohydrate diets have demonstrated improved physical performance [33,66].

Up to 30% of the energy content of protein is utilised for diet induced 'non-shivering' thermogenesis. This makes protein relatively 'wasteful' of energy, whereas values for carbohydrate (5-10%) and fat (0-3%) show greater energy efficiency [67]. These findings, coupled to the fact that protein induces satiety more than carbohydrate or fat, imply that a low protein diet should be used at HA to achieve energy balance, at least until acclimatised.

It has been suggested that the macronutrient proportions listed in Table 4 are utilised to make up diets for consumption by military personnel at HA [38]. Additionally, a supplementary carbohydrate drink [33] and free access to fluids should be provided.

Carbohydrate	60%
Fat	22-25%
Protein	12-15% (1.2-1.5 g kg^{-1} during strenuous activity)

Table 4. Recommended macronutrient proportions in a HA diet

In the UK military, the basic operational ration pack is the Multi-Climate Ration (MCR) which is designed to provide all energy and nutrients to sustain a soldier for a period of 24 hours. If all of the components of the MCR are consumed, it will provide a mean (across all menu variants) energy intake of 4098 kcal, which includes 651 g of carbohydrate, 130 g of protein and 92 g of fat [68]. The MCR thus contains even more than the recommended proportion of carbohydrate, but a relatively high proportion of protein. A trial ration for use at HA has been tested by UK Special Forces. This 6000 kcal ration with six main menus, is comprised mostly of dehydrated meals (to reduce weight) with the addition of high calorie snacks and drinks. The macronutrient breakdown is 55% carbohydrate (minimum), 30-35% fat and 12-15% protein [69].

Conclusions

Basal metabolic rate, daily energy expenditure, substrate utilisation and physical performance are all affected by acute HA exposure. These effects interact and vary according to level and nature of activities, dietary intake and composition and degree of altitude and non-altitude related behaviours, adaptations and illnesses. The mechanisms underlying metabolic responses to HA are not fully understood. More research is clearly required in this complex and challenging arena.

A variety of mission-critical metabolic factors operate at HA. A key message for commanders and military medical personnel is that soldiers need not lose weight if the physiological and pathological responses that predispose to weight loss at HA are mitigated and, indeed, aggressively counteracted. Although HA creates an environment that promotes negative energy balance (with consequent weight loss) this is a potentially modifiable parameter, albeit difficult to achieve. There is, however, a trade-off between the benefits of maintaining energy balance and other factors that affect performance (e.g. weight of rations, postprandial concentration, gut discomfort after eating). Critically, performance is protected by increased energy intakes in association with a high carbohydrate ration, even if energy balance is not achieved.

Acknowledgements

With thanks to Dr Jo Fallowfield who reviewed the manuscript.

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