

Abstract

High-altitude mountaineering is a discipline that combines rock climbing, ice climbing, ski mountaineering, and glacier travel (Twight et al., 1999). Interest in high-mountain climbing is growing every year, including among mountaineers at the amateur level (Salisbury et al., 2021). Exposure to hypobaric hypoxia conditions (>3,000 MASL) induces a range of adverse effects on the human body; however, knowledge of these mechanisms remains incomplete. The aim of the study was to assess the impact of a high-altitude expedition on dietary habits, health status, physical performance, and gut microbiome composition in alpinists. The theoretical introduction to this series of scientific publications was a review article on nutrition, hydration, and dietary supplementation of mountaineers in high-altitude environments.

The study included 17 male participants aged 30.29 ± 5.8 years, with a climbing experience of 10 ± 5 years, training on average 8 ± 3 hours per week, and participating in expeditions to peaks ranging from 5,000 to 8,000 MASL, lasting on average 34 ± 6 days (including 26 ± 6 days above 3,000 MASL). To determine the energy and nutrient value of both habitual and high-altitude diets, a 3-day weighed food record method was used. Dietary habits and attitudes during the expedition were assessed using a custom-designed questionnaire. Body composition was analyzed using dual-energy X-ray absorptiometry (DEXA), and selected indicators of general health status were assessed (hematology and blood biochemistry, urinalysis, stool testing, and intestinal permeability). Aerobic performance was evaluated using a graded exercise test to exhaustion, while anaerobic performance was assessed using the Wingate test for upper and lower limbs. Metagenomic sequencing was used for microbiome analysis. Bioinformatic and statistical analyses enabled the evaluation of changes in microbiome composition and function, as well as their correlations with physiological and dietary parameters. Assessments of health status, body composition, physical performance, and gut microbiome were performed twice - before and after the expedition.

The literature review indicated that, although numerous studies have examined the effects of high-altitude exposure on human physiology, relatively few publications address nutritional aspects under high-altitude conditions. This highlights the need to raise athletes' awareness of proper nutrition, hydration, and supplementation strategies, which may contribute to improved well-being, optimal health, enhanced physical performance, and greater chances of success during alpine expeditions. It is also important to ensure appropriate dietary support, including nutrition education and the individualization of dietary recommendations, even during the preparation stage.

The analysis of habitual diets showed that alpinists are at risk of negative energy balance and/or low energy availability. Most climbers provided adequate amounts of macro- and micronutrients in their habitual diet, except for selenium, iodine, and vitamins D and K. Nutritional issues observed during high-altitude expeditions primarily involved insufficient energy intake relative to increased demands, inadequate protein intake, and excessive fat consumption. Energy deficits should be compensated by increasing carbohydrate intake and/or appropriate supplementation. Due to observed deficiencies in many micronutrients, increased intake of potassium, calcium, magnesium, iron, zinc, selenium, iodine, as well as vitamins A, D, C, folate, and K is recommended. If dietary intake cannot meet requirements, supplementation should be considered. The analysis of food group consumption at high altitude showed that climbers most frequently consumed sugar and sweets, nuts and seeds, and cereal products (both whole-grain and refined). Conversely, due to limited availability, they least often consumed vegetables, fruits, eggs, milk and dairy products, butter and cream, fish, and meat. Supplement use during the expeditions appeared appropriate and consistent with current recommendations for climbers, particularly regarding carbohydrates, protein, vitamins and minerals, omega-3 fatty acids, caffeine, and probiotics. Nonetheless, further research is needed to determine optimal dosages, timing, and long-term effects of supplementation on high-altitude adaptation. Supplementation should always be tailored individually in consultation with healthcare professionals such as physicians and dietitians.

High-altitude expeditions resulted in unfavorable changes in body composition, including reductions in body weight, muscle mass, lean mass in both upper and lower limbs, and appendicular lean soft tissue index (ALST), which could negatively affect physical performance. Given the adverse environmental factors characteristic of high-altitude conditions and the elevated metabolic rate, special attention should be paid to optimizing energy intake and individualized supplementation to mitigate these effects. Staying at high altitude did not negatively affect climbers' health status, except for a decrease in HDL cholesterol levels. However, insufficient dietary intake of iron, folate, and vitamin D was reflected in their blood test results. Most climbers presented normal intestinal permeability markers before the expedition, although some showed elevated zonulin levels despite normal alpha-1-antitrypsin concentrations. More than three weeks of hypoxia exposure (>3000 MASL) negatively affected aerobic capacity, anaerobic performance of the lower limbs, and selected indices of anaerobic performance of the upper limbs, despite a noticeable erythropoietic effect.

The composition, species abundance, and number of microbiome functions did not change significantly under high-altitude conditions; however, an increase in the frequency and

abundance of the *glucose and glucose-1-phosphate degradation pathway* was observed, indicating a functional adaptation to increased carbohydrate availability and environmental stress. Correlations observed between microbiome characteristics and selected dietary components, as well as health and performance indicators, support the involvement of the gut microbiome in the adaptive response to high-altitude stress. Nevertheless, these findings require confirmation in larger cohorts and interventional studies. Future research should include long-term analyses of the relationships between diet, gut microbiome, and physical performance under high-altitude hypoxia, conducted in larger populations and through controlled dietary interventions such as the use of pre-, pro-, and synbiotics, or modulation of carbohydrate and micronutrient intake.