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# *From Physiological Stress to Dietary Intervention: Nutritional Strategies for Lowland Migrant Workers at High Altitude*

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***Abstract.*** With the continuous cross-regional flow of the labor force, large numbers of migrant workers from low-altitude regions are entering high-altitude areas to engage in high-intensity physical labor. Due to the lack of long-term genetic and physiological adaptation to hypoxic environments, this population faces pronounced physiological stress. This paper systematically reviews the effects of high-altitude exposure on metabolism, circulation, and oxygen utilization, covering key changes such as metabolic remodeling, increased cardiovascular load, and enhanced oxidative stress, and building on these findings, elucidates the specific requirements of plateau workers for carbohydrates, high-quality protein, iron, and antioxidant nutrients. On this basis, by integrating the traditional food resources and dietary cultures of the Tibetan Plateau, the Andean Plateau, and the Ethiopian Plateau, this paper proposes region-specific dietary strategies that can leverage the advantages of local food resources while compensating for nutritional shortcomings, including fortification of local staple foods, improvement of protein quality, and enhancement of antioxidant supply. This study aims to construct a nutritionally supportive framework with local adaptability and physiological specificity for enterprises operating at high altitude, providing a foundation for improving workers' health status and work performance.

***Keywords:*** High-altitude, Hypoxia, Nutrition, Dietary Strategies

## 1. Introduction

High-altitude regions, historically sparsely populated due to harsh climates and hypoxia, are now seeing large influxes of lowland migrant workers for infrastructure, mining, and military activities. Unlike genetically adapted highland populations (e.g., Tibetans), these workers lack adaptation to hypobaric hypoxia. Within weeks of arrival, they face physiological challenges including sympathetic excitation, increased pulmonary artery pressure, elevated red blood cell count, oxidative stress, and metabolic shifts [1-4]. Long-term exposure can lead to cardiac hypertrophy and cognitive decline [2].

These physiological changes challenge labor efficiency, occupational health, and worker well-being. Existing high-altitude research has focused on natives, military personnel, or athletes, leaving lowland migrant workers, a large population with prolonged exposure and high physical workloads, without a systematic physiological-nutritional perspective or a targeted nutritional intervention framework.

This paper proceeds from physiological changes to a dietary framework. It first outlines key physiological alterations in energy metabolism, muscle, cardiovascular function, and oxygen balance in lowland populations at high altitude, comparing adaptive differences with highland natives. Based on these changes, it analyzes worker requirements for carbohydrates, protein, and micronutrients, linking these needs to traditional dietary resources on the Tibetan, Andean, and Ethiopian Plateaus. Finally, it constructs a unified nutritional framework for enterprises and proposes region-specific intervention schemes for the three plateaus.

## 2. Major physiological effects of harsh high-altitude environments on the human body

High-altitude regions are characterized mainly by low barometric pressure, low oxygen partial pressure, and cold, dry environments, and these challenges exert multi-level, multi-system effects on energy metabolism, cardiovascular regulation, blood oxygen supply–demand balance, and cognitive function in lowland populations. Acute exposure triggers systemic hypoxic stress like hyperventilation, while chronic or repeated exposure induces metabolic remodeling, cardiac structural changes, and hematopoietic adaptation.

### 2.1. Major physiological effects

### 2.1.1. Energy metabolism disorders and oxidative stress

When tissue oxygen partial pressure decreases, mitochondrial volume density increases in a compensatory manner to help maintain ATP production under oxygen-limited conditions [4]. However, decreased cristae density and electron transport chain impairment can induce energy metabolism disorders and elevate Reactive Oxygen Species (ROS) generation [5]. Enhanced mitochondrial electron leakage and a declining antioxidant system further exacerbate ROS generation and sustain oxidative stress [5].Concurrently, the body upregulates glycolysis and glucose mobilization to stabilize energy supply [6]. This is evidenced by increased glucose production and upregulated lactate recycling, demonstrating an enhanced dependence on carbohydrate substrates [7]. In addition, elevated leptin and decreased ghrelin levels suppress appetite and reduce energy intake, exacerbating these metabolic disorders [8].

### 2.1.2. Decrease in skeletal muscle mass

Prolonged hypobaric hypoxia significantly impacts skeletal muscle, manifesting as atrophy, reduced fiber size, and decreased strength. This results from excessive activation of the ubiquitin-proteasome and calpain pathways, where protein degradation outpaces synthesis, leading to muscle fiber disarray and reduced fatigue resistance [9]. This catabolic shift is driven by HIF-1α stabilization, NF-κB activation, and upregulated inflammatory cytokines, which promote ubiquitin-pathway-mediated breakdown. Although the rate of muscle protein synthesis increases, it is still unable to reverse the trend of loss. Macroscopically, this results in reduced fiber cross-sectional area in both slow- and fast-twitch muscles, leading to decreased physical capacity, endurance, and overall exercise performance [6,10,11].

#### 2.1.3. Increased cardiovascular load and structural changes

The initial cardiac response involves sympathetic nervous excitation, disrupting autonomic balance and leading to elevated heart rate, increased blood pressure, and decreased Heart Rate Variability (HRV) [12]. Chronically, the heart faces an increased load, manifesting as pulmonary hypertension and right ventricular strain, which can progress to right ventricular hypertrophy [13]. In workers with long-term intermittent exposure, these changes can manifest as myocardial hypertrophy, diastolic dysfunction, and myocardial fiber remodeling [14]. One-year exposure has been associated with altered cardiac chamber size, diminished diastolic function, and persistent pulmonary hypertension, indicating significant health risks [15].

#### 2.1.4. Imbalance of blood oxygen supply and demand and increased pressure on the hematopoietic system

Decreased arterial oxygen partial pressure stimulates erythropoietin and angiogenic factors, promoting erythropoiesis and neovascularization [16]. This increases hemoglobin and red blood cell concentrations, enhancing oxygen-carrying capacity but placing cumulative stress on the hematopoietic system and, long-term, burdening the cardiovascular system through increased blood viscosity

#### 2.1.5. Decline in cognitive function and emotional status

Reduced blood oxygen saturation restricts cerebral oxygen supply, significantly impacting cognitive function. This decline is attributed to hypoxia interfering with neuronal energy metabolism, inducing glutamate toxicity and calcium overload, and causing free-radical oxidative stress [17]. In addition, a clinical study conducted in a region at an altitude of 3000 m indicated that the probability of early cognitive impairment in stroke patients at high altitude is significantly higher than in lowland areas, reflecting higher oxygen sensitivity of brain tissue in high-altitude regions [18].

### 2.2. Physiological differences between indigenous highlanders and migrant workers

The major highland groups that have lived for generations at high altitude Tibetans, Sherpas, and Andeans exhibit marked physiological differences from lowland migrant workers. Sherpas enhance oxygen delivery through low blood viscosity and nitric-oxide-mediated vasodilation and vascularization, contrasting with the lowland strategy of increasing red blood cell count [4]. Sherpas also have higher lung volumes, resulting in greater pulmonary ventilation and better pulmonary diffusing capacity. In contrast, Andeans employ an adaptive mechanism similar to plains dwellers, with higher hemoglobin concentrations and red blood cell counts [19]. Additionally, cellular oxidative stress responses remain relatively low in highland populations. These differences stem from both long-term physiological adaptation and genetic evolution, such as EPAS1 and EGLN1 gene mutations in Tibetans that facilitate hypoxic adaptation. Such insights provide crucial evidence for intervention design, emphasizing that highland dietary practices must be adapted with consideration of genetic and structural disparities between populations.

## 3. Correlation analysis between physiological changes and nutritional needs

Under high-altitude exposure, individuals undergo significant changes in physiological status, which have substantial impacts on workers' life experience, work efficiency, and health and well-being;

based on the physiological responses summarized above, this section proposes corresponding nutritional intervention recommendations to reduce the impacts of these physiological changes on work and daily life.

### 3.1. Dietary interventions targeting major physiological impacts at high altitude

Hypoxia-induced oxidative stress and energy metabolism disorders increase fatigue and delay recovery, impairing labor efficiency and operational safety. Ensuring adequate carbohydrate and antioxidant intake is therefore essential. Carbohydrates provide the most oxygen-efficient pathway for ATP production, making them the preferred energy substrate under hypoxic conditions. Carbohydrates should therefore account for over 60% of total energy intake in high-altitude workers' diets. To counter oxidative stress, consumption of antioxidant-rich foods is recommended. Supplementation with vitamin E, vitamin C, and carnitine has been shown to help counteract oxidative stress and hemolysis [20,21]. Chronic hypoxia activates enzyme systems that intensify muscle protein breakdown and skeletal muscle atrophy. Neither increasing protein intake alone nor increasing carbohydrate intake alone has been shown to effectively reduce muscle loss [22,23]. Branched-chain amino acid intake can reduce lean body mass loss during short-term high-intensity activity. Sufficient carbohydrates must also be provided to prevent protein from being diverted to gluconeogenesis. Given the compensatory increase in protein synthesis at high altitude, higher protein intake is conducive to muscle preservation [24]. Enhanced sympathetic activity at high altitude increases heart rate, blood pressure, and right heart load while decreasing HRV. Enhancing nitric oxide supply through nitrate-rich foods or L-arginine can improve exercise endurance, heart rate recovery, and high-altitude adaptation [25,26]. In addition, a series of studies has shown that omega-3 fatty acids have been confirmed to alleviate cardiovascular oxidative stress, suppress excessive inflammation, and prevent arrhythmias and thrombosis. Enhanced red blood cell production at high altitude requires dietary provision of hematopoietic substrates. Iron-rich foods should be ensured, along with vitamin C to enhance iron absorption, and folate and vitamin $B_{12}$ to support red blood cell synthesis. High-altitude exposure impairs cognitive capacity and emotional stability, manifesting as decreased memory and attention and increased irritability and depression, which directly endanger operational safety and work performance. Nutritional interventions should ensure the brain's glucose supply through adequate carbohydrates. B vitamin supplementation can improve memory function under hypoxia, while antioxidant nutrients mitigate oxidative stress effects on neurons. Tea consumption may alleviate high-altitude-induced mood disturbances.

### 3.2. Evaluation of traditional high-altitude dietary resources: nutrition-oriented local adaptation analysis

Traditional high-altitude diets, optimized over generations, embody indigenous wisdom regarding plateau-appropriate nutrition. Analyzing the dietary structures of the Tibetan, Andean, and Ethiopian Plateaus and their local advantages can inform nutritional interventions for lowland migrant workers.

#### 3.2.1. Dietary characteristics of the Tibetan Plateau

The Tibetan diet centers on highland barley and yak products. Highland barley, consumed mainly as tsampa and Tibetan noodles, provides dietary fiber, starch, and trace minerals, including iron, copper, manganese, and selenium, which support energy stability and hematopoiesis, while its low glycemic index sustains glucose supply [27]. Yak meat offers high protein, iron, and zinc for hemoglobin maintenance. Yak milk contains protein, fat, lactose, and bioactive substances with anti-hypoxic, anti-fatigue, and antioxidant properties.

### 3.2.2. Traditional dietary characteristics of thE Andean Plateau

The Andean diet features quinoa, amaranth, potatoes, maize, and alpaca or llama meat. Quinoa offers high protein content and a complete amino acid profile, serving as an ideal source of both protein and carbohydrates [28]. Llama and alpaca meat provide protein, iron, zinc, and B vitamins with relatively low fat content, reducing the oxygen cost of fat metabolism.

### 3.2.3. Traditional dietary characteristics of the Ethiopian Plateau

The Ethiopian diet centers on injera, a fermented teff flatbread. Meat consumption is limited due to economic factors, but teff itself provides high protein and minerals, including iron, calcium, zinc, and magnesium. Injera is typically consumed with legumes, vegetables, or meat, achieving a balanced nutrient profile [29].

### 3.2.4. Common patterns and nutritional insights of the three high-altitude dietary systems

Despite cultural and resource differences, the three high-altitude dietary systems share common patterns: staple crops—highland barley, quinoa, and teff—rich in protein, minerals, and fiber; and animal foods providing low-fat protein, iron, and zinc to support muscle function and hematopoiesis. These diets, characterized by special grains, high protein, high energy, and low fat, offer valuable references for designing culturally adaptable and scientifically sound interventions for lowland migrant workers. By integrating the strengths of these traditional foods and addressing potential gaps in modern diets, more sustainable nutritional strategies can be developed, tailored to workers' distinct exposure patterns and task types.

## 3.3. Exposure patterns of migrant labor populations on the three major plateaus

Migrant worker populations vary across plateaus in altitude, work type, and material supply, necessitating context-specific nutritional design. Representative cities were selected from each plateau to comparatively summarize migrant population characteristics.

Table 1. Representative high-altitude migrant labor populations in major plateaus

| City | Plateau | Altitude | Population | Characteristics of migrant population | Main origin regions | Main types of work |
|---|---|---|---|---|---|---|
| Lhasa(china) | Tibetan Plateau | 3650m | 867,900(2020) | Plains populations (Han ethnicity) account for 26.86% | Neighboring provinces such as Sichuan, Gansu | Infrastructure construction, urban services |
| La Rinconada | Andean Plateau | 5100m | 30,000–50,000 | Constitute the majority of the population, mostly seasonal migrants | Nearby highland and lowland areas in Peru | Gold mining, ore transport, processing and smelting |
| Debre Berhan | Ethiopian Plateau | 2840m | 188,000 | Large inflow of displaced and migrant populations | Nearby mid- and low-altitude rural areas | Construction, services, peri-urban agriculture |

Table 1 summarizes news reports, literature, and government data on migrant workers from the plains in representative cities such as Lhasa, La Rinconada, and Debre Berhan. It can be seen that the Tibetan Plateau is relatively maturely developed, mainly hosting long-term resident infrastructure and service workers, whereas the Andean Plateau is dominated by seasonally mobile workers engaged in high-intensity mining. On the Ethiopian Plateau, migrant populations are mainly regionally mobile; despite these differences, all three regions share common exposure patterns of coming from low altitude, migrating to high altitude for work, and bearing heavy labor loads, which reflects the practical necessity of constructing a unified physiological response model and nutritional requirement framework on top of differentiated contexts, and also provides a basis for designing locally adapted dietary intervention strategies within a unified framework.

## 4. Design of dietary intervention strategies and region-specific adaptation schemes

Based on the systematic analysis of changes and dietary interventions in energy metabolism, skeletal muscle protein turnover, cardiovascular load, hematopoietic pressure, and cognitive function presented above, this paper proposes comprehensive dietary design principles for high-altitude workers. They mainly comprise three aspects. First, energy density should be increased to ensure that blood glucose is maintained at an adequate level while addressing insufficient carbohydrate intake caused by subjective loss of appetite. Second, nutrient diversity should be enhanced, particularly including protein, iron, and vitamins B, C, and D, to support the maintenance of muscle, strengthen hematopoiesis, and reduce the impact of oxidative stress; third, rationality is required, meaning that food ingredients should be composed of locally available raw materials and raw materials whose costs are bearable for enterprises.

### 4.1. Design of nutrient sources and food exchange tables

To maintain nutritional consistency across variable supply chains, foods are divided into five categories: energy, protein, iron, antioxidant, and ω-3 fatty acid sources (Table 2). This allows logistical departments to adjust food structures flexibly without altering overall nutrient intake, accommodating cost, transport, and cultural factors.

Table 2. Nutrient-equivalent food exchange system for high-altitude diet planning

| Nutrient module | Target servings | Target nutrient amount | Equivalent food options | Main nutritional characteristics and significance |
|---|---|---|---|---|
| Energy-providing | 3-4 | ≈ 350 kcal | Highland barley 100 g; quinoa 95 g; teff flour 95 g; potatoes 450 g | Meet major energy and carbohydrate needs, provide about 60% of total energy, and reduce additional oxygen consumption |
| Protein | 9–10 | ≈11g | Yak/beef 50 g; alpaca meat 50 g; cooked legumes 130 g; cow's milk 330 mL; quinoa 85 g | Ensure protein supply in environments with high labor intensity and high risk of muscle breakdown; legumes and quinoa as alternatives |
| Iron | 2-3 | ≈ hematopoietic effect of 50 g red meat | Red meat 50 g; teff flour 40–50 g; quinoa ≈ 90 g; cooked legumes ≈ 140 g | Maintain hematopoietic capacity, particularly suited for high-altitude workers at high risk of anemia and engaged in intense labor |

Table 2. (continued)

| | | | | |
|---|---|---|---|---|
| Antioxidant | 2-3 | qualitative | One serving dark leafy vegetables; 20-30g raisins/ blueberry raisins; 1-2 cups of tea | Counteract sharply increased oxidative stress and systemic inflammatory responses in hypoxic environments |
| ω-3 | 1-2 | Provide essential fatty acids | Flaxseed 10 g; walnuts 15-20g; yak milk 200–300 mL | Alleviate cardiovascular and nervous system stress under hypoxic conditions |

## 4.2. Region-specific high-altitude diet design

Within a unified nutritional requirement framework, dietary designs in different regions need to simultaneously consider local supply-chain conditions; this section takes the three major plateaus as examples and proposes locally adaptive dietary schemes for each.

### 4.2.1. Dietary design for tHe Tibetan Plateau

On the Tibetan Plateau, traditional diets are based on highland barley, buckwheat, yak meat, and yak dairy products, but antioxidants depend mainly on yak milk; intake of vitamin C, folate, and dark leafy vegetables is insufficient; and butter tea can raise blood glucose in the short term but is not conducive to long-term maintenance of stable blood glucose. It is recommended to retain highland barley and yak meat as the main components of the dietary structure to utilize local supply-chain advantages and meet needs for iron, carbohydrates, and protein, while adding dark leafy vegetable soups and dried fruits to ensure antioxidant supply. Between meals, workers are advised to consume tsampa to maintain blood glucose and reduce oxygen consumption.

### 4.2.2. Dietary design for The Andean Plateau

Traditional dietary design on the Andean Plateau is based on quinoa, potatoes, and legumes, with sufficient plant-source protein but relatively little animal-source protein, and insufficient iron intake, which in the long term is unfavorable for high-altitude workers' adaptation to hypoxic environments. This paper suggests adding a fixed daily protein supply to the dietary scheme by importing relatively low-cost meat through the supply chain and incorporating it in small amounts into daily meals so as to ensure a stable animal protein supply and improve the quality of the dietary protein supply.

### 4.2.3. Dietary design fOr the Ethiopian Plateau

Diets on the Ethiopian Plateau are centered on teff flatbread (injera) accompanied by legume sauces; this staple structure provides adequate protein and iron supply, but has serious gaps in antioxidant and fat-rich foods. This paper recommends adding dehydrated vegetables and small amounts of meat to workers' diets to reasonably provide sufficient nutrients under manageable transportation and raw material costs.

## 4.3. Implementation recommendations for enterprises

In the course of operating enterprises at high altitude, enterprises should, within limited budgets, construct a nutritional support system that can be maintained over the long term to ensure the well-being and work efficiency of migrant workers and to avoid medical overload, personal injury, and unexpected work stoppages. In this paper, local grains are used as the main components of staple units, which can significantly reduce transportation costs and reduce nutritional instability arising from supply fluctuations; by incorporating meat, legumes, and dried fruits into standardized protein units and iron-effect units, enterprises can provide essential nutrients to workers at relatively controlled costs and thus alleviate high-altitude physiological stress. At the same time, adding between-meal intake helps workers maintain endurance and reduce fatigue accumulation.

## 5. Conclusion

Starting from high-altitude hypoxia in lowland populations, this study links energy metabolism remodeling, skeletal muscle protein loss, increased cardiopulmonary load, elevated hematopoietic pressure, and cognitive–emotional function decline into a nutritional intervention demand chain and, on this basis, constructs an operable dietary intervention framework. The food exchange table converts key nutrients into interchangeable combinations, providing standardized tools for enterprises on the three plateaus that accommodate regional food resources and cost constraints. This approach reduces occupational health risks, including fatigue, anemia, and oxidative stress; improves work performance; and lowers costs from disease and injuries. At a macro level, it may alleviate pressure on high-altitude medical resources by mitigating acute and chronic health damage at the source. This study has several limitations. Evidence for nutritional design lacks multi-level, long-term studies on metabolic regulation, hematopoietic homeostasis, muscle mass changes, and cardiovascular remodeling in lowland migrant populations. Existing research is predominantly short-term or small-scale, lacking rigorous controlled trials. The paper does not account for variations in physiological states across different exposure patterns, durations, or individual differences. These factors require future investigation. Future research should conduct larger-scale, long-term randomized controlled trials to verify the physiological and economic benefits of nutritional interventions in real-world settings, and develop food fortification and formula food systems suited to high-altitude conditions. Through collaboration among research institutions, enterprises, and public health departments, standardized nutritional guidelines for high-altitude workers can be gradually formed, allowing nutritional interventions to truly be transformed into sustainable means of improving workers' health, enhancing regional labor productivity, and achieving long-term social benefits.

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