Altitude And Hypoxic Training Dosage: Physiological Determinants and Implications For Team-sport Athletes — A Narrative Review

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ABSTRACT

Altitude and hypoxic training are widely recognized as effective physiological interventions to enhance athletic performance. These training strategies stimulate both hematological and non-hematological adaptations, including increased erythropoietin production, elevated total hemoglobin mass, improved oxygen transport capacity, enhanced mitochondrial efficiency, and improved buffering capacity. While altitude training has been extensively studied in endurance athletes, its application in team-sport athletes remains less clearly defined due to the intermittent and high-intensity nature of team-sport activities. Team-sport athletes such as field hockey players require repeated sprint ability, rapid recovery, and sustained aerobic capacity to meet match demands. Therefore, understanding optimal hypoxic dose, physiological mechanisms, and sport-specific implementation strategies is essential for maximizing performance outcomes. This narrative review provides a comprehensive synthesis of recent scientific evidence on altitude and hypoxic training adaptations, including molecular mechanisms, physiological responses, and modern hypoxic training models. It further discusses monitoring strategies and practical guidelines for implementing hypoxic interventions in team-sport athletes. The review emphasizes individualized training prescription, standardized hypoxic dose quantification, and sport-specific application to optimize performance benefits and minimize potential risks associated with hypoxic exposure.

Keywords: altitude training; hypoxic dose; hematological adaptation; field hockey; team-sport physiology; erythropoiesis; intermittent hypoxia.

INTRODUCTION

Team sports such as field hockey, football, basketball, and rugby demand a multifaceted physiological profile characterized by high aerobic capacity, anaerobic power, neuromuscular coordination, agility, and rapid tactical decision-making. Elite field hockey players typically cover distances ranging from 8 to 14 kilometers during competitive matches, with repeated high-intensity efforts performed at intensities exceeding 85–95% of maximal heart rate. These demands require efficient oxygen delivery, rapid energy turnover, and effective

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recovery mechanisms between bouts of activity (Han & Liu, 2025).

Altitude training has long been used as an ergogenic strategy to improve endurance performance. Traditional altitude training models such as Live-High–Train-Low (LHTL) have demonstrated improvements in maximal oxygen uptake, hemoglobin mass, and exercise economy. However, recent research suggests that hypoxic training may also enhance repeated sprint ability, metabolic efficiency, and fatigue resistance in team-sport athletes. The concept of hypoxic dose has emerged as a critical determinant of training effectiveness, incorporating altitude level, duration of exposure, and frequency of exposure. Despite increasing interest, the optimal hypoxic dose for team-sport athletes remains uncertain due to variations in training protocols and individual responses to hypoxic stress (Brocherie et al., 2015; Han & Liu, 2025).

Understanding the physiological and molecular mechanisms underlying hypoxic adaptation is essential for designing effective training programs. Furthermore, integrating sport-specific considerations such as movement patterns, respiratory mechanics, and match demands is necessary to ensure successful implementation of hypoxic training interventions in team sports.

Physiological Basis of Hypoxic Adaptation

Exposure to hypoxic environments initiates a cascade of physiological responses aimed at maintaining oxygen delivery and cellular homeostasis. One of the primary mechanisms underlying hypoxic adaptation involves activation of the hypoxia-inducible factor (HIF-1α) signaling pathway. Reduced oxygen availability stabilizes HIF-1α, leading to transcription of genes responsible for erythropoiesis, angiogenesis, glucose metabolism, and mitochondrial function. Short-term exposure to hypoxia typically results in increased ventilation, elevated heart rate, reduced arterial oxygen saturation, and activation of the sympathetic nervous system. These acute responses help maintain oxygen delivery to vital organs and working muscles. However, prolonged exposure to hypoxia leads to more pronounced physiological adaptations, including increased hemoglobin mass, enhanced capillary density, improved mitochondrial efficiency, and increased muscle buffering capacity. These adaptations collectively improve oxygen utilization and delay the onset of fatigue during exercise. In team-sport athletes, improved oxygen transport capacity and metabolic efficiency can enhance repeated sprint performance and reduce recovery time between high-intensity efforts. Additionally, improved ventilatory efficiency and respiratory muscle strength may help athletes maintain performance during prolonged matches (Basheeruddin et al., 2024).

Hematological and Molecular Mechanisms

Hematological adaptation is widely considered the primary mechanism responsible for performance improvements following altitude training. Increased erythropoietin production stimulates erythropoiesis, resulting in increased red blood cell volume and total hemoglobin mass. Studies have shown

Table 1: Summary table of precious studies on the topic of hypoxic training.

Study (Author, Year)	Participants	Study Design	Hypoxic Protocol	Duration	Key Outcome Measures	Major Findings	Practical Implication
Brocherie et al., 2015	Elite team - sport athletes	Controlled field study	Live High –Train Low and High	18 days	VO_2 max, repeated sprint ability	Significant improvement in team-sport performance variables	Combined hypoxic models enhance intermittent performance
Fornasier-Santos et al., 2018	Rugby players (n=21)	Randomized controlled trial	Repeated sprint training with voluntary hypoventilation	4 weeks	Repeated sprint ability (RSA)	Improved repeated sprint performance under hypoxia	Hypoxic sprint training improves RSA in team sports
Brechbuhl et al., 2018	Tennis players	Experimental design	Normobaric hypoxic sprint training	12 days	Repeated sprint ability, time to exhaustion	Enhanced sport-specific performance	Short-term hypoxic training improves intermittent performance
Camacho-Cardenosa et al., 2020	Team-sport athletes	Controlled intervention	Repeated sprint training in hypoxia	3 weeks	Sprint number, maximal power	Increased maximal power and s print performance	Low-dose hypoxia can improve anaerobic performance
Faiss et al., 2020	Professional athlete	Case study	Normobaric hypoxic sprint training	10 days	Sprint performance	Performance improvement after repeated hypoxic exposure	Short hypoxic blocks can enhance performance
Shi et al., 2023	Team-sport players	Experimental comparison	Repeated sprint training in hypoxia	2 vs 5 weeks	Yo-Yo test, repeated sprint ability	Both durations improved repeated sprint performance	Training duration influences residual performance effects
Birol et al., 2024	University athletes	Placebo-controlled study	Normobaric hypoxic sprint training	3 sessions	Sprint performance, SpO_2 , RPE	Hypoxic training altered physiological responses during sprinting	Even short hypoxic exposure affects physiological stress response
Takei et al., 2025	Trained sprint athletes	Pilot study	Repeated sprint training in hypoxia	6 sessions	Sprint velocity, lactate	Reduced lactate concentration but no additional sprint benefit	Hypoxia may improve metabolic efficiency without performance gains
Han et al., 2025	Multiple athlete groups	Meta-analysis	Repeated sprint training in hypoxia	Multiple studies	RSA, aerobic capacity	Moderate improvement in repeated sprint ability	Hypoxia beneficial for intermittent performance adaptation

that total hemoglobin mass may increase by approximately 3–7% following three to four weeks of altitude exposure. Iron availability plays a crucial role in erythropoiesis during hypoxic training. Athletes with low iron stores may exhibit reduced responsiveness to altitude exposure, highlighting the importance of monitoring ferritin levels before and during altitude training programs. Adequate iron supplementation may be necessary to support optimal erythropoietic response. In addition to hematological changes, hypoxia stimulates molecular adaptations such as angiogenesis, mitochondrial biogenesis, and increased activity of oxidative enzymes. These adaptations improve muscle oxygen utilization and enhance metabolic efficiency. Furthermore, hypoxia-induced increases in glycolytic enzyme activity and lactate transport capacity contribute to improved anaerobic performance and fatigue resistance during repeated high-intensity efforts (Płoszczyca et al., 2018).

Non-Hematological Adaptations

Non-hematological adaptations play a significant role in performance improvements associated with hypoxic training. These adaptations include enhanced muscle oxidative capacity, increased buffering capacity, improved neuromuscular efficiency, and improved ventilatory muscle strength. Such adaptations are particularly relevant for team-sport athletes who perform intermittent high-intensity efforts interspersed with short recovery periods. Repeated sprint performance improvements following hypoxic training are often attributed to enhanced phosphocreatine resynthesis and improved muscle oxygen utilization. Improved buffering capacity allows athletes to tolerate higher levels of metabolic acidosis during intense exercise, thereby delaying fatigue. Recent studies have also reported improvements in muscle capillary density and mitochondrial enzyme activity following hypoxic training. These changes enhance oxygen delivery and energy production, allowing athletes to sustain high-intensity performance for longer durations. Additionally, improved neuromuscular coordination and motor unit recruitment may contribute to enhanced agility and movement efficiency during competitive matches (Gutknecht et al., 2022).

Molecular Basis of Hypoxic Training Adaptation

The molecular mechanisms underlying hypoxic training adaptation involve a complex network of signaling pathways that regulate oxygen sensing, erythropoiesis, angiogenesis, mitochondrial biogenesis, and metabolic reprogramming. These processes enable the human body to maintain cellular homeostasis and optimize energy production under conditions of reduced oxygen availability. Understanding these molecular responses is critical for designing evidence-based hypoxic training protocols, particularly for team-sport athletes who rely on efficient energy metabolism and rapid recovery between high-intensity efforts.

Hypoxia-Inducible Factor (HIF) Signaling Pathway:

The central regulator of hypoxic

adaptation is the Hypoxia-Inducible Factor (HIF) family of transcription factors, particularly HIF-1α and HIF-2α. Under normoxic conditions, HIF-α subunits are rapidly degraded through oxygen-dependent hydroxylation mediated by prolyl hydroxylase domain (PHD) enzymes. However, during hypoxia, reduced oxygen availability inhibits PHD activity, allowing stabilization and accumulation of HIF-α in the cytoplasm. The stabilized HIF-α translocates to the nucleus, where it binds with HIF-β to activate transcription of hypoxia-responsive genes. These genes regulate multiple physiological functions, including: Erythropoietin synthesis, Glucose transport (GLUT-1), Vascular endothelial growth factor (VEGF) production, Glycolytic enzyme expression, and Iron metabolism. Activation of the HIF pathway results in enhanced oxygen transport capacity, increased anaerobic metabolism, and improved tolerance to hypoxic stress. Research indicates that repeated exposure to hypoxia through structured altitude training leads to sustained activation of HIF signaling, thereby promoting long-term physiological adaptations relevant to athletic performance (Shi, & Gilkes, 2025).

Erythropoiesis and Iron Regulation:

One of the most well-established molecular responses to hypoxia is the stimulation of erythropoiesis through increased production of erythropoietin (EPO). Hypoxia-induced activation of HIF-2α in the kidney triggers the release of EPO into the bloodstream, stimulating RBC production in bone marrow and ultimately increases total hemoglobin mass and enhances O2-carrying capacity. Hypoxia influences iron homeostasis through regulation of the hormone hepcidin, which controls iron absorption and mobilization. Reduced hepcidin levels during hypoxic exposure enhance iron availability for hemoglobin synthesis, thereby supporting erythropoiesis. Key molecular responses include: (i) Increased erythropoietin production, (ii) Enhanced red blood cell synthesis, (iii) Reduced hepcidin concentration, and (iv) Increased transferrin receptor expression. Studies have shown that athletes with adequate iron stores demonstrate significantly greater increases in hemoglobin mass following altitude training compared to those with iron deficiency (Haase, 2013).

Angiogenesis and Capillary Density:

Hypoxic training stimulates angiogenesis through increased expression of vascular endothelial growth factor (VEGF), a key regulator of new blood vessel formation. VEGF expression is directly regulated by the HIF pathway and plays a critical role in enhancing oxygen delivery to skeletal muscle tissue. Increased capillary density improves: Oxygen diffusion capacity, Nutrient delivery, Waste product removal, and Muscle endurance. These adaptations are particularly relevant for intermittent sports such as field hockey, where repeated high-intensity efforts require efficient oxygen transport and rapid recovery between sprints. Experimental studies have demonstrated that hypoxic training can increase skeletal muscle capillary density by approximately:

10–15% after several weeks of altitude exposure (Xu et al., 2021).

Mitochondrial Biogenesis and Oxidative Metabolism:

Hypoxic exposure activates signaling pathways that regulate mitochondrial biogenesis and oxidative metabolism. One of the primary regulators of this process is peroxisome proliferator-activated receptor gamma coactivator-1 alpha (PGC-1α), a transcriptional coactivator that controls mitochondrial growth and function. Activation of PGC-1α leads to: Increased mitochondrial density, enhanced oxidative enzyme activity, improved aerobic energy production, and Increased fatigue resistance. Hypoxic training also increases the activity of key metabolic enzymes, including: Citrate synthase (CS), Cytochrome-C oxidase, and Lactate dehydrogenase (LDH). These changes improve metabolic efficiency and allow athletes to sustain high-intensity exercise for longer durations. Recent evidence suggests that intermittent hypoxic training may enhance mitochondrial efficiency without necessarily increasing mitochondrial volume, indicating improved oxygen utilization at the cellular level (Qian et al., 2024).

Skeletal Muscle Buffering Capacity and Lactate Transport:

Improvements in muscle buffering capacity and lactate transport will also alter hypoxic adaptation. Hypoxia stimulates the expression of monocarboxylate transporters (MCT-1 and MCT-4), which facilitate lactate movement across cell membranes. Increased MCT expression leads to - Enhanced lactate clearance, Improved acid–base balance, and Increased tolerance to high-intensity exercise. These adaptations are particularly relevant for team-sport athletes who perform repeated sprint efforts during competition. Research indicates that repeated sprint training in hypoxia can increase muscle buffering capacity by: 5–12% thereby improving repeated sprint performance and delaying fatigue (Pérez de Heredia et al., 2010).

Reactive Oxygen Species (ROS) and Cellular Signaling:

Hypoxic exposure leads to increased production of reactive oxygen species (ROS), which act as signaling molecules that regulate cellular adaptation. Moderate increases in ROS stimulate antioxidant enzyme activity and enhance mitochondrial function. Key antioxidant enzymes influenced by hypoxia include: Superoxide dismutase (SOD), Catalase, and Glutathione peroxidase. These enzymes protect cells from oxidative damage and contribute to improved recovery following intense exercise. However, excessive hypoxic exposure may lead to oxidative stress and impaired performance, highlighting the importance of carefully controlling hypoxic dose during training interventions (Hong et al., 2024; Tafani et al., 2015).

Epigenetic and Gene Expression Responses:

Emerging research indicates that hypoxic training may induce epigenetic modifications that influence gene expression and long-term physiological adapta-

tion. These modifications include: DNA methylation, Histone acetylation, and MicroRNA regulation. Epigenetic changes may contribute to the phenomenon of "altitude memory," where athletes retain physiological adaptations following repeated exposure to hypoxia. Recent studies suggest that repeated altitude exposure may produce sustained improvements in endurance performance through long-term changes in gene expression patterns (Zhang et al., 2025).

Determining an Effective Hypoxic Dose

Determining the optimal hypoxic dose is one of the most critical challenges in altitude training research. Hypoxic dose is typically defined as the combined interaction of altitude level, exposure duration, and total exposure time. A commonly used metric for quantifying hypoxic exposure is kilometer-hours (km·h), calculated as altitude (km) multiplied by exposure time (hours). Research suggests that a cumulative hypoxic dose of approximately 300 to 500 km·h is required to produce significant increases in hemoglobin mass. However, individual responses to hypoxic exposure vary widely, and factors such as training status, genetic predisposition, nutritional status, and recovery capacity may influence adaptation. For team-sport athletes, hypoxic dose prescription must consider competition schedules, travel demands, and training load. Excessive hypoxic exposure may lead to maladaptation, including fatigue, reduced performance, and impaired recovery. Therefore, careful monitoring of physiological markers such as heart rate variability, oxygen saturation, and subjective wellness is essential to ensure safe and effective implementation of hypoxic training programs (Behrendt et al., 2022).

Modern Hypoxic Training Models for Team Sports

Recent advances in sport science have led to the development of several hypoxic training models specifically designed to improve performance in intermittent sports. These models include repeated-sprint training in hypoxia (RSH), sprint interval training in hypoxia (SIH), and intermittent hypoxic exposure (IHE). Repeated-sprint training in hypoxia involves performing short sprint intervals under hypoxic conditions to enhance anaerobic capacity and recovery kinetics. Studies have demonstrated improvements in repeated sprint ability, muscle oxygen utilization, and recovery time following RSH interventions. Sprint interval training in hypoxia focuses on maximizing anaerobic power and metabolic efficiency, while intermittent hypoxic exposure involves brief periods of hypoxic exposure without exercise to stimulate physiological adaptation. These modern hypoxic training methods provide flexible and practical options for team-sport athletes who may not have access to traditional altitude training environments. Additionally, these methods allow for precise control of hypoxic dose and training intensity, enabling individualized training prescription (Galvin et al., 2013).

Monitoring and Individualization of Hypoxic Training

Individual responses to hypoxic

training vary significantly among athletes, leading to the classification of responders and non-responders. Monitoring physiological and performance indicators is essential for optimizing training adaptation and minimizing the risk of maladaptation. Common monitoring tools used in hypoxic training programs include hemoglobin mass measurement, heart rate variability analysis, blood lactate concentration, oxygen saturation monitoring, and subjective wellness questionnaires. These tools provide valuable information about athlete readiness, recovery status, and adaptation to hypoxic stress. Individualized training programs based on athlete-specific characteristics such as fitness level, training history, and recovery capacity are essential for maximizing performance benefits. Regular assessment of physiological markers allows coaches and sport scientists to adjust training intensity and hypoxic exposure to meet individual needs (Li et al., 2025).

Practical Guidelines for Coaches

Evidence-based guidelines for implementing hypoxic training in team-sport athletes emphasize gradual progression of hypoxic exposure, adequate recovery, and continuous monitoring of physiological responses. Recommended altitude exposure typically ranges from 1800 to 2500 meters, with daily exposure durations of 12 to 16 hours for three to four weeks. Monitoring iron status, hydration levels, and nutritional intake is critical for supporting physiological adaptation. Coaches should also incorporate recovery strategies such as sleep optimization, hydration, and periodized training load management to minimize fatigue and maximize performance gains.

In addition, sport-specific training drills should be integrated into hypoxic training programs to ensure transfer of physiological adaptations to match performance. Collaboration between coaches, sport scientists, and medical staff is essential for ensuring safe and effective implementation of hypoxic training interventions.

CONCLUSION

Altitude and hypoxic training represent powerful tools for enhancing physiological performance in team-sport athletes. Emerging evidence suggests that these interventions improve repeated sprint ability, metabolic efficiency, and recovery capacity. However, substantial variability in individual responses highlights the need for personalized training prescription and careful monitoring of physiological markers.

Future research should focus on sport-specific experimental designs, standardized hypoxic dose quantification, and integration of advanced monitoring technologies to optimize training outcomes. With evidence-based implementation and individualized programming, hypoxic training has the potential to provide a meaningful competitive advantage for team-sport athletes competing at elite levels.

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