

Research

Physiological Adaptation and Transition to Pathology: Lessons from Exercise Physiology and Ergonomics in Extreme Environments

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Abstract:

Extreme environmental conditions such as cold exposure, hypoxia, and physical load challenge human physiological homeostasis and may trigger a transition from adaptive responses to pathological processes. Understanding these mechanisms is essential not only for environmental and occupational physiology but also for clinical medicine, where similar physiological constraints occur during surgery, critical illness, and rehabilitation. This review integrates findings from three complementary research projects conducted at the Jožef Stefan Institute investigating field-based ergonomics, peripheral vascular responses to cold and hypoxia, and metabolic adaptations during prolonged normobaric hypoxic exposure. The studies demonstrate that environmental stressors interact through systemic physiological mechanisms affecting thermoregulation, microcirculation, energy metabolism, and functional performance. Cold-induced vasodilation (CIVD) emerges as a dynamic marker of physiological adaptability, while hypoxia influences both peripheral vascular regulation and whole-body metabolic balance. Together, these findings provide translational insights into vascular dysfunction, tissue perfusion, metabolic resilience, and perioperative physiology, highlighting the continuum between environmental adaptation and clinically relevant pathology.

Keywords: Cold-induced vasodilation; Hypoxia; Environmental physiology; Ergonomics; Metabolism; Thermoregulation; Surgery; Vascular function; Adaptation

1. Introduction

Human physiological systems continuously adapt to environmental challenges in order to maintain homeostasis. Exposure to cold, hypoxia, and prolonged physical activity represents a substantial stress that activates integrated cardiovascular, metabolic, thermoregulatory, and neuroendocrine responses (Mazzeo, 2008; Cheung, 2010). While these adaptive mechanisms are generally protective, excessive or prolonged exposure may lead to maladaptation and contribute to pathological processes. Understanding the factors that determine whether physiological stress results in successful adaptation or dysfunction remains a central objective of integrative physiology (Tipton et al., 2017, 2021; Keramidias et al., 2010, 2014; Kounalakis, 2010; Mekjavic et al., 2012, 2016, 2022, 2023).

Research conducted in extreme environments offers a unique opportunity to investigate mechanisms that are highly relevant to clinical medicine. Conditions such as impaired tissue perfusion, hypothermia, metabolic stress, and reduced oxygen availability frequently occur during major surgical procedures, critical illness, and recovery following trauma (Sessler, 2016; Ince, 2005). Consequently, environmental physiology provides a useful framework for studying the continuum from physiological adaptation to pathology.

2. Field Ergonomics and Physiological Performance Under Environmental Stress

The study demonstrated that physiological strain was determined primarily by individual physical capacity rather than by absolute workload alone. Considerable inter-individual variability was observed despite identical environmental conditions and equipment loads. These findings emphasize the importance of personalized ergonomic assessment and illustrate the complex interaction between environmental demands, physical workload, and individual physiological reserve (Knapik et al., 2004; Amon, 2007).

3. Peripheral Vascular Responses to Cold and Hypoxia

The second project investigated cold-induced vasodilation (CIVD), a protective peripheral vascular response that occurs during prolonged exposure to cold. CIVD is characterized by periodic increases in blood flow and skin temperature following an initial phase of vasoconstriction. This phenomenon is believed to reduce local cold injury while preserving tissue oxygenation and viability (Lewis, 1930; Daanen, 2003; Amon, 2009).

The results revealed that normobaric hypoxia impaired peripheral temperature responses in the toes, whereas finger CIVD responses remained largely unchanged. These findings suggest regional differences in vascular adaptation and indicate that lower extremity circulation may be more susceptible to reduced oxygen availability. Importantly, aerobic training combined with altitude acclimatization improved CIVD responses, demonstrating that peripheral vascular adaptation is modifiable and influenced by physiological conditioning (Amon et al., 2012a; Felicijan et al., 2008).

Although CIVD has traditionally been investigated within the field of environmental physiology, its broader clinical significance is increasingly recognized. Variability in CIVD responses may reflect differences in vascular health, metabolic status, body composition, and physiological reserve (Daanen, 2003; Tsoutsoubi et al., 2023). Consequently, CIVD may represent a valuable integrative marker of microvascular function and individual adaptability to physiological stress.

4. Metabolic Adaptation During Prolonged Hypoxia

Comprehensive metabolic assessments included body composition analysis, meal tolerance testing, appetite regulation, hormonal responses, and measurements of resting energy expenditure. The findings demonstrated that hypoxia consistently induced a negative energy balance through a combination of increased energy expenditure and reduced energy intake. This effect was accompanied by alterations in appetite-regulating hormones and increased sympathetic nervous system activity (Mekjavic et al., 2016; Kayser, 1994; Westerterp et al., 1992).

In normal-weight participants, hypoxia prevented the increase in fat mass that occurred during normoxic exposure despite relatively modest changes in total body weight. In overweight individuals, similar reductions in appetite and increases in energy expenditure were observed. However, evidence of early insulin resistance was also detected, suggesting that metabolic responses to hypoxia may differ according to baseline metabolic status (Mekjavic et al., 2016).

5. Clinical and Translational Implications

The physiological challenges encountered in extreme environments closely parallel those observed in perioperative medicine and critical care. Surgical patients frequently experience controlled hypothermia, transient tissue hypoperfusion, metabolic stress, and altered oxygen delivery. Consequently, understanding adaptive responses to environmental stress may provide valuable insights into mechanisms underlying postoperative complications and recovery (Sessler, 2016; Ince, 2005; Carli & Scheede-Bergdahl, 2015).

Particularly relevant is the role of microvascular function in maintaining tissue viability. The ability to preserve peripheral circulation during environmental stress may reflect broader vascular resilience that influences wound healing, tissue regeneration, and recovery from surgical interventions (Ince, 2005). Similarly, the metabolic adaptations observed during hypoxic exposure provide insights into mechanisms regulating performance and energy balance, insulin sensitivity, and physiological reserve (Mekjavic et al., 2012; Mekjavic et al., 2016).

Cold-induced vasodilation emerges from these studies as a potential integrative biomarker linking vascular responsiveness, thermoregulatory capacity, and overall physiological adaptability (Amon et al., 2012b; Daanen, 2003; Tsoutsoubi et al., 2023).

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Conflicts of Interest: The author declares no conflict of interest.

References

1. Amon M. Ergonomic assessment of soldier during a 12-kilometer hike. Thesis. Ljubljana. 2007. Available at: <https://plus.cobiss.net/cobiss/si/sl/data/cobib/2875755>
2. Amon M. Effects of "Sleep high-train low" hypoxic training on cold induced vasodilatation (CIVD) response in fingers and toes. Master thesis. Ljubljana. 2009. <https://doi.org/10.1089/ham.2011.1044>
3. Amon M. Normobaric hypoxia: metabolic responses following 10-day hypoxic confinement. Doctoral dissertation. Ljubljana: Jožef Stefan International Postgraduate School. 2012a. Available at: <https://revis.openscience.si/IzpisGradiva.php?lang=slv&id=13614>
4. Amon M, Keramidas ME, Kounalakis SN, Mekjavic IB. The effect of a sleep high-train low regimen on the finger cold-induced vasodilation response. *High Alt Med Biol.* 2012; 13:32-39. DOI:10.1089/ham.2011.1044
5. Carli F, Scheede-Bergdahl C. Prehabilitation to enhance perioperative care. *Anesthesiol Clin.* 2015; 33:17-33. DOI:10.1016/j.anclin.2014.11.002
6. Cheung SS. *Advanced Environmental Exercise Physiology*. Champaign, IL: Human Kinetics. 2010
7. Cheung SS, Daanen HA. Dynamic adaptation of the peripheral circulation to cold exposure. *Microcirculation.* 2012; 19:65-77. DOI:10.1111/j.1549-8719.2011.00126.x
8. Daanen HA. Finger cold-induced vasodilation: A review. *Eur J Appl Physiol.* 2003; 89:411-426. DOI:10.1007/s00421-003-0818-2
9. Debevec T, Amon M, Keramidas ME, Kounalakis SN, Pisot R, Mekjavic IB. Normoxic and hypoxic performance following 4 weeks of normobaric hypoxic training. *Aviat Space Environ Med.* 2010; 81:387-93. DOI: 10.3357/ase.2660.2010.
10. Felicijan A, Golja P, Milcinski M, Cheung SS, Mekjavic IB. Enhancement of cold-induced vasodilatation following acclimatization to altitude. *Eur J Appl Physiol.* 2008; 104:201-206. DOI:10.1007/s00421-008-0720-z
11. Ince C. The microcirculation is the motor of sepsis. *Crit Care.* 2005; 9:S13-S19. DOI:10.1186/cc3753
12. Kayser B. Nutrition and high altitude exposure. *Int J Sports Med.* 1992; 13:S129-S132. DOI:10.1055/s-2007-1024616

13. Keramidas ME, Kölegård R, Mekjavic IB, Eiken O. Acute effects of normobaric hypoxia on hand-temperature responses during and after local cold stress. *High Alt Med Biol.* 2014; 15:183-91. DOI: 10.1089/ham.2013.1131.
14. Keramidas ME, Debevec T, Amon M, Kounalakis SN, Simunic B, Mekjavic IB. Respiratory muscle endurance training: effect on normoxic and hypoxic exercise performance. *Eur J Appl Physiol.* 2010; 108:759-69. DOI: 10.1007/s00421-009-1286-0.
15. Kounalakis SN, Keramidas ME, Amon M, Eiken O, Mekjavic IB. A 10-day confinement to normobaric hypoxia impairs toe, but not finger temperature response during local cold stress. *J Therm Biol.* 2017; 64:109-115. DOI: 10.1016/j.jtherbio.2017.01.009.
16. Knapik JJ, Reynolds KL, Harman E. Soldier load carriage: historical, physiological, biomechanical, and medical aspects. *Mil Med.* 2004; 169:45-56. DOI:10.7205/milmed.169.1.45
17. Lewis, T. Observations upon the reactions of the vessels of the human skin to cold. *Heart.* 1930; 15:177-208. <https://ci.nii.ac.jp/naid/10004343165>
18. Mazzeo RS. Physiological responses to exercise at altitude : an update. *Sports Med.* 2008; 38:1-8. DOI:10.2165/00007256-200838010-00001
19. Mekjavic IB, Norheim AJ, Friedl KE. Human performance and medical treatment during cold weather operations - synthesis of a symposium. *Int J Circumpolar Health.* 2023 ; 82:2246666. DOI: 10.1080/22423982.2023.2246666.
20. Mekjavic IB, Debevec T, Amon M, Keramidas ME, Kounalakis SN. Intermittent normobaric hypoxic exposures at rest: effects on performance in normoxia and hypoxia. *Aviat Space Environ Med.* 201; 83:942-950. DOI: 10.3357/ase.3332.2012.
21. Mekjavic IB, Amon M, Simpson EJ, Kölegård R, Eiken O, Macdonald IA. Energy Intake of Men With Excess Weight During Normobaric Hypoxic Confinement. *Front Physiol.* 2022; 12:801833. DOI: 10.3389/fphys.2021.801833.
22. Mekjavic IB, Amon M, Kölegård R, Kounalakis SN, Simpson L, Eiken O, Keramidas ME, Macdonald IA. The Effect of Normobaric Hypoxic Confinement on Metabolism, Gut Hormones, and Body Composition. *Front Physiol.* 2016; 7:202. DOI: 10.3389/fphys.2016.00202.
23. Tipton MJ, Corbett J, Eglin CM, Mekjavic IB, Montgomery H. In pursuit of the unicorn. *Exp Physiol.* 2021; 106:385-388. DOI: 10.1113/EP089147.
24. Sessler DI. Perioperative thermoregulation and heat balance. *Lancet.* 2016; 87:2655-2664. DOI:10.1016/S0140-6736(15)00981-2
25. Tsoutsoubi L, Ioannou LG, Alba BK, et al. Central versus peripheral mechanisms of cold-induced vasodilation: a study in the fingers and toes of people with paraplegia. *Eur J Appl Physiol.* 2023; 123:1709-1726. DOI:10.1007/s00421-023-05175-7
26. Tipton MJ, Collier N, Massey H, Corbett J, Harper M. Cold water immersion: kill or cure? *Exp Physiol.* 2017; 102:1335-1355. DOI: 10.1113/EP086283. Epub 2017 Sep 21. PMID: 28833689.
27. Westerterp KR, Kayser B, Brouns F, Herry JP, Saris WH. Energy expenditure climbing Mt. Everest. *J Appl Physiol.* 1992; 73:1815-1819. DOI:10.1152/jappl.1992.73.5.1815