High-Altitude Adaptive Mechanisms in Yak

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1. Introduction

Domestic yaks (*Poephagus grunniens L.)* are an integral part of the socio-economic and cultural life of the yak rearing nomadic communities of the Trans-Himalayan region. These regions are characterised by extreme environmental conditions, including very low temperatures below freezing point upto -40°C, hypoxia, steep slopes, strong ultraviolet radiation, rugged terrain and low biomass availability [1]. However, yaks, by virtue of their years of evolution in high altitude, have evolved some distinct morphological, physiological, biochemical and geneticadaptations to thrive in high-altitude environments (Figure 1) [2]. These adaptation mechanisms have made yak one of the only livestock that is sustaining the livelihood of these highland nomads in regions where there is little to no arable land for agriculture.

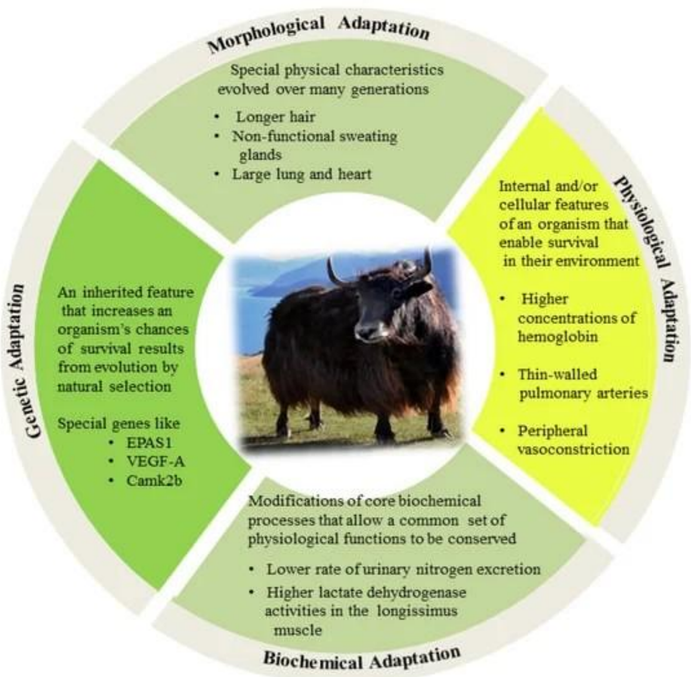

Fig. 1. Schematic representation of adaptive mechanisms of yak to high-altitude
(Adapted from *Ayalew et. al., 2021*)

Comparative studies of yak with lowland livestock like cattle has also provided insights on the numerous traits that equip yak for survival at high altitude and has contributed in understanding the evolutionary adaptation of yak. These adaptive traits roughly include large hearts, large lungs increasing the pulmonary alveolar area per unit area [3], lack of hypoxic pulmonary vasoconstriction, lack of functioning sweat glands, increased foraging ability, strong environmental senseand high energy metabolism, oxygen transport and improved thermoregulation [4,5].

2. Adaptation mechanisms:

Yaks are well adapted to the harsh climate and hypoxia occurring under high altitude grazing conditions of the Himalayan mountains. However, it is unclear to which degree different yaks tolerate these conditions and how they perform and behave under these circumstances. Species living at high altitudes are exposed to strict selection pressures and physiological challenges owing to harsh environmental conditions such as thin air, cold temperatures, ultraviolet exposure, and low pressure [6].

2.1 Morphological Adaptations:

Animals undergo morphological modifications over many generations in order to improve their fitness in a particular environment. Yaks possess larger lungs and hearts relative to their body size, enabling them to efficiently absorb and transport oxygen at lower atmospheric pressures. They have a thick outer hair coat and a fine down undercoat, which helps conserve heat in the harsh, cold climate of high altitudes. Yaks have broad hooves that help them navigate the challenging, rocky terrain of their habitat. Their compact body shape reduces surface area to volume ratio, minimizing heat loss. The absence of functional sweat glands enhances cold tolerance.

2.2 Physiological Adaptations:

Physiology can be seen as the systems and functions that enable organisms to cope with internal challenges (such as exercise, growth, and reproduction) and external stress (for instance, changes in temperature, oxygen levels, water accessibility, salinity, pressure, radiation, and heavy metals, etc.). Yaks have numerous anatomical and physiological traits that equip them for life at high altitude, including large lungs and hearts [7], lack of hypoxic pulmonary vasoconstriction [8], increased foraging ability [9], strong environmental sense and high energy metabolism [7,10]. Yaks have a reduced response to the constriction of blood vessels in the lungs under hypoxic conditions, allowing for better blood flow and oxygen delivery. Yaks have a keen sense of smell and can efficiently forage for food in sparse, high-altitude environments. Yaks have a high energy metabolism, which helps them maintain body temperature and activity in the cold, hypoxic environment. Yaks can digest and retain nitrogen more efficiently than cattle, especially at low dietary nitrogen intake, which is common in high-altitude environments. The proliferation of red blood cells, which carry oxygen, is enhanced in yaks, allowing them to effectively transport oxygen in the lower oxygen environment. The haemoglobin in yak blood has a higher affinity for oxygen, enabling them to efficiently extract oxygen from the air at high altitudes.

2.3 Biochemical Adaptations:

The frigid, low-oxygen environments of high-altitude ecosystems place significant metabolic requirements on warm-blooded vertebrates. Grasping how these high-altitude endotherms manage the dual challenges of low oxygen and cold offer valuable perspectives on the mechanism of adaptive evolution. Biochemical adaptations offer intriguing insights into how living organisms function and how they adapt to maintain physiological processes amid a wide variety of environmental circumstances. As a biochemical adaptation, yaks have modification in the haemoglobin structure to improve oxygen affinity with increased average platelet volume and plasma fibrinogen concentrations.

2.4 Genetic Adaptations:

Studies have identified specific genes and pathways that are associated with yaks' adaptation to high altitude, including genes involved in red blood cell proliferation, energy metabolism, and oxygen sensing. Yaks possess genes that help them adapt to cold stress, including genes related to metabolism and energy production. Currently, existing research has recognized the EPAS1, EGLN1, and PPARA genes as significant in high-altitude adaptation [11, 12]. Additionally, whole genome re-sequencing has revealed genomic variants and functional pathways associated with adaptation in Indian yak populations [13]. Yaks have evolved specific adaptations to detect and respond to hypoxic stress, which is a critical factor at high altitudes.

2.5 Epigenetic basis of high-altitude adaptation:

Yaks also exhibit unique epigenetic adaptations to thrive at high altitudes, such as modifications to their histones and DNA methylation patterns, which affect genes involved in energy metabolism, hypoxia response, and nutrition absorption. Studies have revealed that yaks and lowland cattle have different DNA methylation patterns, as well as ncRNAs that are expressed differently in yaks. These findings imply that epigenetic modification additionally contributes to yaks' ability to adapt to high altitude.

3. Conclusion

Domesticated ruminants residing at elevations where human communities exist can play a role in the cross-species approach to validate established or discovering new mechanisms of adaptation to low oxygen levels. Besides genome-wide adaptive alterations at the DNA sequence level, gene expression as an intermediate phenotype connecting DNA sequences and physiological characteristics uncovering the molecular pathways/networks involved in genetic adaptation. Therefore, further studies need to be conducted to reveal the high-altitude adaptation of the yaks and the role of various potential genes and proteins should be looked upon.

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