Pathophysiology and Treatment of High-Altitude Pulmonary Vascular Disease

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It is estimated that >140 million people live above 2500 m in various regions of the world. There are many challenges to living at high altitude, but chronic exposure to alveolar hypoxia is prominent among them. Inspired Po2 falls from ~150 mmHg at sea level to ~100 mmHg at 3000 m and 43 mmHg on the summit of Everest (8400 m). The body responds by hyperventilating, increasing resting heart rate, and stimulating red cell production in an attempt to maintain the oxygen content of arterial blood at or above sea level values. However, hypoxic pulmonary vasoconstriction (HPV) and vascular remodeling, together with increased erythropoiesis, place an increased pressure load on the right ventricle (RV). How well healthy humans adapt to hypoxia depends on their rate of ascent to altitude, the severity and duration of their exposure, and their genetic background.

Pathophysiology of Acclimatization to Hypoxia

Pulmonary Vascular Response to Hypoxia

For most mammals, including humans, a rise in pulmonary artery pressure (PAP) is an early and inevitable consequence of ascent to high altitude. Resting mean PAP increases along a parabolic curve from 15 mmHg at 2000 m to ~30 mmHg at 4500 m. The exceptions and interindividual variation in the magnitude of response offer a natural experiment that might provide insight into fundamental underlying mechanisms (vide infra).

The initial rise in PAP on exposure to hypoxia is attributed to HPV. With chronic hypoxia, other mechanisms that likely drive vascular remodeling soon contribute to the elevated pressure (Figure 1A). After 2 or 3 weeks of hypoxia, there is little response to rebreathing 100% oxygen, indicating a structural resistance to pulmonary blood flow rather than one based solely on increased vasomotor tone. A fall in PAP on re-exposure to a normal oxygen environment is evident in rats monitored by telemetry over days after removal from a hypoxic chamber (Figure 1B) and is also documented in humans.

Pulmonary Arteriolar Vasoconstriction Dominates the Acute Pulmonary Vascular Response to Hypoxia

Oxygen tension is a major regulator of pulmonary vascular tone and a physiological mechanism for matching perfusion with ventilation. A fall in alveolar Po2 is the main stimulus for HPV, but a reduction in mixed venous and bronchial arterial Po2 may also contribute. Ventilation of intact lungs with a hypoxic gaseous mixture (eg, fraction of inspired oxygen=0.10) leads to acute pulmonary vasoconstriction throughout the pulmonary vascular bed, including nonmuscular arterioles, capillaries, and veins, but is most pronounced in small pulmonary arterioles.

HPV has at least 2 phases (Figure 1A). An initial constrictor response that starts within seconds and reaches a maximum within minutes is followed by a sustained phase, which develops after 30 to 120 minutes. A transient phase of vasodilation may be observed linking the two, and a third phase of even more pronounced vasoconstriction can occur after 120 minutes. The phases are regulated, at least in part, by different signaling pathways.

Alveolar capillaries have been proposed as a site for oxygen sensing with propagation of the hypoxic signal by endothelial membrane depolarization to upstream arterioles in a connexin 40-dependent manner. However, the recapitulation of contraction to hypoxia in cultured pulmonary artery smooth muscle cells, the effector cells, indicates that an oxygen-sensing mechanism is intrinsic to these cells. Both mitochondria and nicotinamide adenine dinucleotide (phosphate) oxidases have been suggested as oxygen sensors. A change in the levels of reactive oxygen species is thought to be important, but there is a lack of agreement regarding whether the signal is an increase or decrease in reactive oxygen species (Figure 2).

Differences in techniques used contribute to the different observations, but the spatial distribution of reactive oxygen species signaling may also be significant.

The second phase of HPV is influenced by endothelial cell function. The endothelium releases a variety of vasoactive mediators, such as endothelin 1, prostacyclin, and nitric oxide (NO; Figure 3) and their production is perturbed by hypoxia. For example, oxygen is a substrate for NO

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(Circulation. 2015;131:582-590. DOI: 10.1161/CIRCULATIONAHA.114.006977.)

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Circulation is available at http://circ.ahajournals.org

DOI: 10.1161/CIRCULATIONAHA.114.006977

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Chronic global alveolar hypoxia is accompanied by structural remodeling of pulmonary vessels. This has been described in a number of species, including rat, cow, and humans, although some species seem resistant. All of the layers of the vascular wall, including fibroblasts, are involved in the remodeling (Figure 4), but the hallmark of the vascular response to chronic hypoxia is increased muscularization of distal vessels with extension of muscle into previously unmuscularized arterioles.

Hypoxia leads to changes in endothelial cell membrane properties that compromise barrier function, resulting in an influx of plasma proteins that may activate vascular wall proteases. In addition, mechanical stress, blood-borne and locally produced factors, and the recruitment of circulating cells act collectively to drive the vascular remodeling of small and large pulmonary vessels, with increasing recognition of the role of inflammation (Figure 4). Rapid expansion of the adventitial vasa vasorum serves to facilitate the arrival of these cells.

HIFs and nuclear factor-kB are key transcriptional regulators of the proliferative and inflammatory responses to hypoxia. Pulmonary hypertension in hypoxic mice haploinsufficient for HIF-1α (Hif1α+/−) or HIF-2α (Hif2α+/−) is attenuated. Conversely, gain-of-function mutations in HIF-2α are associated with the development of pulmonary hypertension in mice and humans.

Although in part caused by and adaptive to the increase in hemodynamic stress, the vascular remodeling contributes to and sustains the elevated PAP. Indeed, the structural changes take a considerable time to resolve on return to a sea-level oxygen environment and may persist in some form. The extent to which the structural changes in pulmonary resistance vessels infringe on the lumen and contribute a physical obstruction to blood flow (ie, the argument being that vascular growth is outward rather than inward) and the extent of vascular rarefaction in response to chronic hypoxia are unclear. These may vary between species.

Mechanisms other than narrowing of the vessel lumen are relevant to this discussion, specifically the contribution of changes in vascular compliance. Changes in the stiffness of proximal vessels leads to changes in the propagation of high-energy pulsatile waves. These are transmitted to the microcirculation, where they might perpetuate or potentially even cause the microcirculatory changes, as well as contribute to the burden on the RV.

Cardiac Response to Chronic Hypoxia

Studies of healthy subjects exposed to hypoxia report an increase in resting heart rate and an initial increase in cardiac output in an attempt to maintain oxygen delivery to tissues. After 2 to 3 days of hypoxia, stroke volume falls. Heart rate remains elevated, and so cardiac output remains at or just below sea level. Oxygen delivery to tissues is maintained by increased oxygen extraction. The roles of activation of the sympathetic nervous system, hypovolemia (from hyperventilation and increased diuresis), hypocapnia (from hyperventilation), and myocardial contractility in this response are difficult to discern. On the whole, myocardial contractility is preserved, although reversible reductions in cardiac mass and myocardial phosphocreatine/ATP have been documented in healthy volunteers after a 17-day trek to 5300 m. Right heart failure is a risk in some previously healthy individuals, precipitated by more extreme pulmonary

**Figure 4.** Contribution of hypoxic pulmonary vasoconstriction (HPV) and vascular remodeling to the rise in pulmonary artery pressure (PAP) in chronic hypoxia. A. The initial rise in PAP in hypoxia is driven by HPV. The pressor response to hypoxia does not return to baseline on normoxia in isolated perfused rabbit lungs, even if the perfusate is replaced to remove hypoxia-stimulated circulating vasoactive factors. Modified from Weissmann et al. B. Elevated PAP in a telemetry rat takes days to return to baseline after removal from 2 weeks in a hypoxic chamber.
vascular responses to hypoxia, and also in the context of chronic mountain sickness (CMS), from pronounced erythrocytosis and fluid retention (from relatively higher $P_{\text{co}_2}$).

Exercise

Exercise capacity is reduced at altitude, even after acclimatization, but the contribution of pulmonary hypertension is controversial. Exercise capacity is reduced at altitude, even after acclimatization, but the contribution of pulmonary hypertension is controversial.49,50 PAP increases more sharply with the increase in cardiac output on exercise at altitude than at sea level.51 This augmented rise in PAP with exercise can persist for some time in acclimatized highlanders on descent to sea level, most likely reflecting structural remodeling of the pulmonary vasculature with chronic exposure.5,8 The increase in PAP may impair gas exchange from interstitial and alveolar edema and reduce maximal cardiac output, leading to a reduction in oxygen transport to exercising muscles.49 However, definitive data from direct measurements of RV function at altitude are few, and not all are convinced that the improvement in exercise capacity at altitude reported with some pulmonary vasodilators is attributed to a reduction in RV afterload.50

Erythropoietic Response to Hypoxia

Exposure to hypoxia leads to changes in blood-$O_2$ affinity and stimulates red cell production in an attempt to improve tissue oxygenation. Increased red cell 2,3 diphosphoglycerate levels have an allosteric effect on hemoglobin, reducing its affinity for $O_2$ and facilitating its release to tissues, although this is at the expense of impairing $O_2$ capture as blood passes through the lungs. Increasing red cell mass also has its downside, as it increases blood viscosity. Little attention has been paid to the contribution of increased blood viscosity to PAP, because the increase in PAP precedes the rise in hemoglobin, and patients...
with polycythemia at sea level do not have pulmonary hypertension. A recent re-evaluation of the effect of increased blood viscosity on PAP measurements at altitude suggests that some correction for hematocrit is important.32,53

Clinical Presentations From Maladaptation to Hypoxia

Variation in Susceptibility to High-Altitude Pulmonary Vascular Disease

The rise in PAP in chronic hypoxia is generally modest, certainly compared with that seen in idiopathic pulmonary arterial hypertension, and is compatible with a normal life at high altitude. However, variation in the pulmonary vascular response to hypoxia is well recognized, both between and within species,16,31,54,55 and in humans the magnitude of HPV can vary 5-fold among individuals.16,55 Extreme responders are at highest risk of presenting acutely on arrival at altitude with high-altitude pulmonary edema (HAPE) or over weeks, months, and years with right heart failure secondary to severe pulmonary hypertension or excessive erythrocytosis.

High-Altitude Pulmonary Edema

The pathognomonic clinical feature is breathlessness accompanied by cough, initially dry but later productive of white and then pink frothy sputum.56,57 Tachycardia, mild pyrexia, and sometimes cyanosis are also evident. The chest radiograph shows pulmonary edema. The condition develops in susceptible individuals within the first 2 to 4 days of arrival at altitudes above 2500 m. It is precipitated by rapid ascent and exercise and is potentially lethal if not treated. The incidence is variously recorded, depending on the subject population, rapidity of ascent, and final altitude; everyone is at risk of HAPE if they ascend fast and high enough. It is caused by exaggerated and uneven HPV leading to high capillary pressures in regions of the lung and an exudation that might invoke a secondary inflammatory response.57-59 Susceptible individuals exhibit a marked rise in PAP on exposure to hypoxia mediated by pulmonary arteriolar vasoconstriction and a greater rise in PAP on exercise in a normal oxygen environment, indicating a hyperactive pulmonary circulation.56

The emphasis in management is on prevention. Travelers should manage their rate of ascent to 300 to 500 m per day along with a day of rest every 3 to 4 days when traveling above 3000 m.56 Pharmacologic measures that have been evaluated and demonstrated efficacy in reducing the incidence of HAPE include slow-release nifedipine (30 mg BID),60 the phosphodiesterase type 5 inhibitor tadalafil (10 mg BID), and dexamethasone (8 mg BID).61 The β2-agonist salmeterol (125 μg BID) by inhalation appears to be less effective.62

When treatment is required, consideration should be given to descent to a lower altitude coupled with supplemental oxygen (2–4 L/min) where possible.56,63 Nifedipine is the standard treatment. A phosphodiesterase type 5 inhibitor may be helpful but has not been formally trialed. There is no role for diuretics. A fully conscious person with mild-to-moderate HAPE may be managed at altitude if the appropriate expertise and facilities are available.

HAPH and Heart Failure

By convention, the definition of HAPH is a resting mean PAP >30 mm Hg.64 This needs revisiting and reconciling with international guidelines for the definition of pulmonary hypertension, which is a resting mean PAP >25 mm Hg.53,65

Data on the prevalence of HAPH are sparse. Prevalence will vary according to altitude and ethnic background, but some 14% of Kyrgyz highlanders have been found to have ECG evidence of right ventricular hypertrophy.66 A much smaller percentage progress to and present with heart failure.

The RV generally copes well with a pressure load, and there is doubt as to whether pressure load itself is sufficient to cause heart failure, suggesting that other factors, such as myocardial hypoxia and neurohumoral factors, are important.67 Nonetheless, pulmonary hypertension progressing to fatal right heart failure, recognized as infantile subacute mountain
sickness, has been described in infants of Chinese Han origin who are born at low altitude and taken to high altitudes.\(^6^8\) They develop heart failure within a few weeks or months and the pathology reveals extreme medial hypertrophy of the small pulmonary arteries accompanied by hypertrophy and dilatation of the RV. Heart failure has also been described in Indian soldiers posted at the high-altitude borders in China\(^6^9\) and occasionally in previously healthy travelers,\(^7^0\) and HAPH is thought to be the major factor.\(^7^1\)

Descent to lower altitude is life saving for severe cases of heart failure. There are a number of potential pharmacologic treatments for managing less severe disease, but few have been formally trialed in HAPH. Phosphodiesterase type 5 inhibitors appear effective at reducing pulmonary vascular resistance,\(^7^2\) and acetazolamide\(^7^3\) and the Rho-kinase inhibitor, fasudil\(^7^4\), are promising. The benefits of endothelin receptor antagonists are less clear.\(^7^5\)\(^7^6\)

**Chronic Mountain Sickness**

The defining feature of chronic mountain sickness (CMS) is excessive erythrocytosis accompanied by neurologic symptoms, such as headache, dizziness, and fatigue.\(^6^4\) By consensus, the hemoglobin should exceed \(\geq 21\) g/dL in men and \(\geq 19\) g/dL in women. Hypoventilation leading to hypoxemia may stimulate red cell production,\(^4\) but an alternative possibility is that polycythemia is the primary abnormality, which, by reducing Pco\(_2\) drive, leads to hypoventilation. Pulmonary hypertension may accompany the polycythemia but is not a prerequisite.

Descent to low altitudes is the best treatment but may not be acceptable to patients for personal reasons. An alternative to phlebotomy is acetazolamide. Acetazolamide (250 mg daily) has been shown to reduce hematocrit, increase PaO\(_2\), and oxygen saturation, and decrease in Paco\(_2\) in CMS, most likely via metabolic acidosis stimulating ventilation.\(^7^3\) Pulmonary
vascular resistance was also reduced and cardiac output increased without a change in pulmonary pressure.

**Insights From Humans Adapted to Hypoxia**

**Variation in Susceptibility to High-Altitude Pulmonary Vascular Disease**

The variation in pulmonary vascular response has a strong genetic basis, which provides the substrate for environmental selection pressures and adaptation to high-altitude living. Tibetans appear less susceptible than recent migrants to HAPH\(^77,78\) and CMS,\(^9\) most likely the result of the living above 3000 m for thousands of years. Data are few, but PAP measurements in ethnic Tibetans living over 3600 m are in the range typical of healthy adults at sea level,\(^77,78\) and postmortem studies show little vascular remodeling.\(^78,80\) A blunted pulmonary vascular pressor response to acute and sustained hypoxia is retained by Tibetans at sea level.\(^81\)

**Recent Genomic Studies in Humans**

A number of attempts have been made to understand adaptation to high-altitude life based on differences in candidate pathways, such as the ability of Tibetans to preserve NO production at altitude\(^82\) and candidate genes,\(^66,83\) but this approach is selective and the data come from small subject numbers. The advent of high-throughput genome sequencing has enabled a less-biased strategy for investigating gene associations. The priority to date has been to compare the genetic architecture of people living at high altitude with that of lowlanders or recent migrants (genome-wide selection scans) rather than to compare well-phenotyped populations with and without pulmonary vascular disease at altitude (genome-wide association studies).

Seven genome-wide selection scans of Tibetan DNA have been reported. All have shown evidence of natural selection for noncoding variants in and around 2 HIF pathway genes,\(^84,86\) EPAS1 (HIF-2α) and EGLN1 (HIF prolyl 4-hydroxylase 2).\(^84,90\) Key to the interpretation of genetic data is robust phenotyping. Tibetans average \(≥1\) g/dL and as much as 3.5 g/dL (ie, \(=10\% to 20\%\)) lower hemoglobin concentration compared with acclimatized lowlanders. At first sight, a paradox, a lower red cell mass by reducing blood viscosity may be an important factor enabling the cardiopulmonary circulation to adapt to high-altitude life. Significantly, the polymorphisms in EPAS1 and EGLN1 in Tibetans correlate with hemoglobin concentration.\(^84,86,88,90\) A high-frequency missense mutation has recently been identified in EGLN1 that encodes a variant prolyl 4-hydroxylase 2 with increased hydroxylase activity under hypoxic conditions that would contribute to this adaptive response.\(^91\)

A genome study in Andeans has found evidence of positive selection for EGLN1 but not EPAS1.\(^92\) Neither were candidates in reported studies in Ethiopian highlanders.\(^93-95\) Moreover, Andeans exhibit a robust erythropoietic response to altitude and polymorphisms identified in EGLN1 in Andeans, albeit different from those in Tibetans, did not associate with hemoglobin level. Analysis of other quantitative traits, such as resting ventilation, hypoxic ventilator response, and oxygen saturation, also show differences between Tibetans and other Asian and European populations studied at the same altitude.\(^96\) It is likely that the Andean and Tibetan populations have developed different genetic adaptations to high-altitude hypoxia, although pathways may converge. In the case of Tibetans, one source of adaptation is likely to be attributed to the introduction of genetic variants from archaic Denisovan-like individuals into the ancestral Tibetan gene pool.\(^97\)

Aside from HIF, genes encoding downstream components of the HIF pathway remain a priori candidates for natural selection to hypoxia. A recent study of single nucleotide polymorphisms in 5 Ethiopian populations at altitude suggest positive selection for BHLHE41, a gene transcriptionally regulated by HIF-1α and with a major regulatory role in the same hypoxia-sensing pathway described in Tibetans, indicative of convergent evolution.\(^99\) Other pathways may emerge from unbiased genome-wide studies in larger population cohorts. Evidence for adaptation outside the HIF family comes from a study of Eurasians exposed to mild-to-moderate hypoxia, where the strongest adaptive signal came from the \(μ\)-opioid receptor-encoding gene (OPRM1, 1.0 × 10\(^{-9}\)).\(^98\)

Whole-genome sequencing of Andean highlanders, 10 with and 10 without CMS, followed by expression studies in fibroblasts identified 2 genes, SENP1 and ANP32D, that exhibit a higher transcription response to hypoxia in CMS subjects.\(^99\) Downregulation of the orthologs of these genes in flies enhanced their survival rates in a hypoxic environment. SENP1 is known to regulate erythropoiesis and SENP1-/- mice die early because of anemia, lending biological plausibility to this gene as a candidate for a role in CMS. There is widely believed to be a genetic predisposition to HAPE, but to date only candidate genes have been examined with no consensus observations.\(^100\)

**Conclusions**

Humans can live a normal life at high altitudes given sufficient time to acclimatize. People who exhibit a marked pulmonary vascular or erythropoietic response to hypoxia identify themselves as at risk of heart failure. Studies in Tibetan people adapted genetically to high altitude highlight the importance of the HIF pathway in determining the magnitude of response, but other pathways may emerge from studies of Tibetan cohorts better phenotyped for pulmonary hemodynamics, as well as studies of other ethnic groups. Considerable progress has been made in understanding the pathology of HAPH, but few drugs studied in animal models have been formally trialed in humans.

**Acknowledgments**

We thank Dr Oleg Pak for his assistance with the figures.

**Sources of Funding**

Drs Wilkins and Zhao are funded by the British Heart Foundation. Drs Weissmann and Ghofrani are funded by the German Research Foundation, Excellence Cluster Cardio-Pulmonary System (EXC 147).

**Disclosures**

None.
References


High-Altitude Pulmonary Vascular Response


**KEY WORDS**: anoxia ▫ genetics ▫ hypertension, pulmonary ▫ vascular remodeling ▫ vasoconstriction
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_Circulation._ 2015;131:582-590
doi: 10.1161/CIRCULATIONAHA.114.006977
_Circulation_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the
World Wide Web at:
http://circ.ahajournals.org/content/131/6/582

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