The role of hypoxia in pulmonary vascular diseases: a perspective

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Voelkel NF, Mizuno S, Bogaard HJ. The role of hypoxia in pulmonary vascular diseases: a perspective. Am J Physiol Lung Cell Mol Physiol 304: L457–L465, 2013. First published February 1, 2013; doi:10.1152/ajplung.00335.2012.—From the discovery of hypoxic pulmonary vasoconstriction, responses to hypoxia have been considered as representative for the many alterations in lung vessels that occur in several chronic lung diseases, including pulmonary hypertension, interstitial pulmonary fibrosis, acute respiratory distress syndrome, and chronic obstructive pulmonary disease. An essential part of preclinical research to explain the pathobiology of these diseases has been centered on the exposure of small and large animals to hypoxia. This review aims to summarize pivotal results of clinical and preclinical research on hypoxia, which still have important implications for researchers today.

PULMONARY HYPERTENSION is defined clinically as a mean pulmonary artery pressure of greater than 25 mmHg. From a clinical perspective, it matters whether the underlying lung vascular abnormalities are progressive and affect the performance of the right cardiac ventricle (94). Hypoxia (i.e., a decreased oxygenation of tissues) causes under most circumstances pulmonary vasoconstriction (96). A disease component attributable to chronic hypoxic pulmonary vasoconstriction is conventionally accepted and assigned a pathobiological role in many chronic lung diseases, including interstitial pulmonary fibrosis, acute respiratory distress syndrome and chronic obstructive pulmonary disease (15, 25, 101). Understandably, the mechanism of hypoxic pulmonary vasoconstriction has fascinated and attracted several generations of investigators. Although many important questions have been answered [e.g., what cell senses the decrease in oxygen tension in the lung? (99)], other fundamental questions related to the signal transduction of hypoxic pulmonary vasoconstriction remain only partially addressed (75, 83).

In most mammals chronic hypoxia causes chronic pulmonary hypertension (CHPH), and the severity of CPHH is remarkably species dependent. Mouse, hamster, guinea pig, and sheep on one end of the spectrum develop only a mild degree of CPHH (27, 97), whereas cattle on the other end develop severe CPHH (88). Early investigators of mechanisms of CPHH already wondered whether, in addition to pulmonary arterial smooth muscle constriction, hypoxia affected the remainder of the lung tissue. They also asked whether lung tissue hypoxia, independent of vasoconstriction, contributes to the development of chronic lung vascular disease and to CPHH.

But in the early days no compelling mechanistic concepts were readily available or acceptable. To some extent the easily observable hypoxic vasoconstriction blocked the view and the mind to envision and investigate vasomotor tone-independent alternatives. That is easily understood because how could one study CHPH without hypoxic pulmonary vasoconstriction? After all Ivan McMurtry had shown that calcium channel blockade prevents acute hypoxic vasoconstriction as well as CPHH (78).

We now know that prevention of CPHH by calcium channel blockers does not eliminate the possibility that chronic hypoxia, i.e., the decreased lung tissue oxygenation, profoundly contributes to the development of chronic pulmonary vascular diseases. For example, the calcium channel blocker nifedipine decreases the lung tissue activity of NF-kB in rats exposed to hypoxia (68). For the field to move forward and to discover vasoconstriction-independent mechanisms, it was necessary during chronic hypoxic exposure not to manipulate hypoxic vasoconstriction. The biology of tissue hypoxia was in its infancy, and physiologists made it clear that hypoxia was distinct from anoxia and ischemia-reperfusion. The present Perspectives attempts to put lung tissue hypoxia into a historical and conceptual framework that should allow us to better understand the impact of chronic hypoxia on lung diseases with lung vascular involvement.

Hypoxic Hypoxia vs. Tissue Ischemia: the Systemic Disease Components

It is useful to distinguish between generalized, total body hypoxia as experienced at altitude due to the low partial pressure of atmospheric oxygen, and localized, regional tissue ischemia, which is the preferred term rather than “hypoxia,” a term often used by tumor biologists when they describe the tumor microenvironment (64). Generalized hypoxic hypoxia, as it occurs at altitude, has both systemic and organ-specific consequences (20, 21). In addition to peripheral vaso-dilation, pulmonary vasoconstriction and activation of a sympathico-adrenergic stress response to increase cardiac output (60), there is activation of the bone marrow and erythropoietin-stimulated red cell production, and there are effects on the immune system. Increased cardiac output and polycythemia are “meaningful” adaptive responses “designed” to improve blood and oxygen delivery to the hypoxic tissues (Fig. 1 and Table 1).

In contrast, tissue ischemia occurs when a hampered blood supply limits local availability of oxygen (hypoxia) and nutrients. Intratumor hypoxia is a critical component of tumorigenesis and is generated by the enhanced demand for blood and nutrients of the rapidly growing cancer cells that are supplied by structurally abnormal and leaky tumor vessels. Regardless, whether the microenvironment oxygenation is impaired as the
The first data indicating that CHPH and inflammation are related was the discovery of lung mast cell hyperplasia in chronically hypoxic rats (38). Lung mast cell hyperplasia also occurs in human idiopathic pulmonary arterial hypertension (PAH) (29), but it still remains unclear today whether resident mast cells multiply around pulmonary hypertensive vessels, or whether the mast cell accumulation is the consequence of a hypoxia- or lung injury-triggered release of mast cells from the bone marrow. Lung mast cell hyperplasia in pulmonary hypertensive lungs provided the initial background and rationale for the search for mediators of hypoxic pulmonary vasoconstriction and mediators of inflammation in the pulmonary hypertensive lung. Indeed, leukotrienes and platelet-activating factor levels were found to be elevated in the lung during hypoxia (48, 61). More recently, mast cells are viewed as repositories of vasoactive factors and growth factors; they also store and release metalloproteases (47).

A reliable model for the study of CHPH is the rat and several hundreds of experimental data have been reported during the last 50 years. It can be shown that within 24 h of exposure to simulated altitude (hypobaric hypoxia) inflammatory cells accumulate in the lungs and a simple readout of this event is the increased activity of lung tissue myeloperoxidase. But is lung inflammation causally related to CHPH or merely an associated event? This question was addressed by Ono et al. (56), who demonstrated that an anti-inflammatory drug that has no effect whatsoever on the pulmonary artery pressure prevented the lung inflammation that develops after hypoxia exposure and the development of CHPH in rats. Whereas the pathogenetic concept of CHPH had initially been summarized as “there is no CHPH without vasoconstriction,” the concept “there is no CHPH without inflammation” was new (56). Subsequently, investigators have moved to the molecular level. FIZZ1 (also known as RELMα or hypoxia-induced mitogenic factor HIMF) has been shown to be released during hypoxia from lung macrophages. HIMF is proinflammatory and proangiogenic via vascular endothelial growth factor (VEGF) and its receptor VEGFR2 (102); in the mouse HIMF also recruits bone marrow cells (36).

Table 1. Hypoxia stress responses and the cancer paradigm (17, 19, 45)

| Proliferation and survival of stem cells (MYC, p53, AKT) |
| Macrophage migration and cytokine production |
| Glycolysis (GLUT 1, PGK1) |
| Angiogenesis (VEGF, PDGF) |
| Inflammatory cell infiltration (SDF1, CXCR4) |
| HIF-1α-dependent expression of p53, Bcl2, p21 in stem cells |

Hypoxia and Inflammation

Following the breakthrough discovery of the oxygen tension-dependent homeostatic master “regulator hypoxia-inducible factor 1α” (HIF-1α) (98) that has provided fundamental and important information, we have been on our way to unravel the complex “biochemistry” of hypoxia (71). Not only can we understand the molecular response of cells to hypoxia, HIF-1α importantly also connects hypoxia and inflammation (26, 54, 56, 66, 87). Indeed, hypoxia and inflammation are inseparably intertwined. “The interest concerning the relationship between hypoxia, an admitted primary trigger for many forms of PH [pulmonary hypertension], and inflammation/inflammatory infiltrates is obvious: frequent observation of the latter pattern in PH might be an argument in favor of a canonical pathophysiological pathway and against a simple epiphenomenon in pulmonary arterial hypertension” (24). Figure 1 only shows a partial list of the genes that are expressed by the binding of the HIF-1α protein to hypoxia response elements contained in the sequence of a large number of genes. An expression map of HIF-dependent genes in endothelial cells has been published (46), but HIF-1α and HIF-2α are not the only transcriptional regulators that are active during hypoxia; for example, PGC-1α is another important transcription factor during hypoxia (63).
Hypoxia can induce Toll-like receptor (TLR) 2 and TLR6 in a HIF-1α-dependent fashion (40) and that activation of these TLRs activates NF-κB (90, 91). Also shown in the figure are the reciprocal activations between NF-κB and HIF-1α (90, 91).

A spillover of chemotactic factors like VEGF, leukotriene B4 (LTB4), FIZZ1, and others, released from the hypoxic lung tissue, may complement direct effects of hypoxia on the bone marrow. One result is mobilization of bone marrow-derived cells (likely including mast cells, mesenchymal precursor cells megakaryocytes, and dendritic cells) and their chemotaxis to the lung. Thus hypoxic/hypoxemic inflammation is clearly a systemic response.

IL-6 has recently received attention as a mediator of CHPH. IL-6 mRNA and protein levels were increased in chronically hypoxic mice. IL-6−/− mice showed less lung tissue inflammation, but the degree of CHPH was only moderately reduced in IL-6 knockout (KO) mice (69). Lung-specific IL-6 overexpression in mice increased the muscularization of small pulmonary arteries and the right ventricular systolic pressure in normoxic mice, indicating that, at least in mice, IL-6 contributes to lung vascular remodeling. However, when lung-specific IL-6 overexpressing mice were exposed to chronic hypoxia, severe CHPH and pulmonary vascular lumen obliteration were observed (80). These two reports taken together suggest that IL-6 is increased in chronically hypoxic lung tissue but not necessary for the development of CHPH. The data also suggest that the combination of excessive IL-6 lung levels together with chronic hypoxia changes the mode of lung vessel remodeling toward angioproliferation. An elegant recent study by Brock et al. (14) connected IL-6 overexpression with decreased expression of the BMPR2 protein which is mutated in patients with familial idiopathic PAH (9), and the authors suggest that IL-6 signaling involves the overexpression of cluster microRNA miR-17–92, as shown in Figure 3A, where the alternative mechanism proposed by Steiner et al. (80) is also depicted (Fig. 3B). Clearly, increased IL-6 expression per se is insufficient to cause lung vascular occlusions, and Steiner et al. show that the second hit of chronic hypoxia is necessary. This raises the question: what is it exactly that chronic hypoxia sets in motion in the setting of elevated IL-6? One scenario is that chronic hypoxia mobilizes bone marrow cells, which “attempt to repair” lung vessels that have a low level expression of the lung vessel-protective BMPR2 protein.

It should not be surprising that one of a variety of systemic effects of hypoxia is the modulation of immune responses [see Nicolls and Voelkel (54) and Voelkel et al. (94) for reviews of this topic]. The hypoxia-induced HIF-1α target VEGF (95) facilitates mobilization of cells from the bone marrow and affects the behavior of B and T lymphocytes (41). As such, VEGF firmly links inflammation and angiogenesis. Hypoxia can be immunosuppressive, inhibit T cell proliferation, and affect regulatory T cell function (100), and hypoxia upregulates HIF-1α mRNA in macrophages (79). Inflammatory cells that have migrated into the hypoxic lungs teleologically speaking may be reacting to activated or injured lung cells, in particular to lung vascular endothelial cells. Activated lung endothelial cells express surface adhesion receptors and participate in inflammatory cell-cell interactions. Here is just one example: endothelial cell production of IL-1 can lead to upregulated expression of HIF-1α, amplifying the effect of tissue hypoxia (Fig. 1). In conclusion, both professional inflammatory cells, like polymorphonuclear leukocytes and macrophages, and nonprofessional inflammatory cells, like endothelial cells and fibroblasts, become part of an inflammatory network during CHPH development. Although it may be a convenient concept, it is not yet clear whether HIF-1α expressed in hypoxic lungs (104) is central to CHPH, because so far experiments have only been conducted with HIF-1α+− mice (105). Although partial HIF-1α deficiency reduces CHPH and polycythemia, the effects of partial HIF-1α deficiency on
inflammation are unknown, and conditional HIF-1α KO mice experiments are still lacking.

_Hypoxia, ROS Generation, and Sphingolipid Metabolism_

Hypoxia stress is associated with the cellular production of reactive oxygen species (ROS) and nitrogen species (92). Superoxide anion, generated via activation of NADPH oxidoreductases (NOX) (23), in particular NOX4 in endothelial cells (73), and H2O2 have been proposed as regulators of hypoxic pulmonary vasomotor tone regulation (3, 34). Again, HIF-1α plays an important role: HIF-1α mediates the expression of NOX-2 and ROS activate HIF-1α (106). Treatment of rats with α-acetylcysteine (NAC) diminishes the severity of CHPH (31); whether NAC also affects hypoxic pulmonary inflammation is unknown.

The sphingolipids sphingosine-1-phosphate (S1P) and ceramide are now increasingly recognized as important regulators of barrier function, apoptosis, and chemotaxis in the context of chronic lung diseases (89). Exogenously administered S1P causes pulmonary vasoconstriction (57), which in the isolated perfused mouse lung depends on Rhokinase activation (84); however, it is unknown whether S1P levels are increased in the chronically hypoxic lung, or whether chronic hypoxia generates a S1P-ceramide imbalance. S1P is catalyzed via sphingosine kinase by phosphorylation of sphingosine, and sphingosine kinase 1 expression is controlled by HIF-1α (76). Cell sources of S1P are red blood cells, platelets, and endothelial cells (36). S1P not only affects endothelial cell barrier function and is vasoactive, it is also cardioprotective (36). In pulmonary artery smooth muscle cells chronic hypoxia increased sphingosine kinase 1 gene expression (2) and S1P and ceramides indeed could play a role in the development of CPHH.

_Endothelial Cell-Mesenchymal Transition_

Endothelial-mesenchymal transition (EndMT) is part of a response-to-injury program that has been investigated in myocardial capillary endothelial cells of the mouse (108), in kidney fibrosis (107), and in cancer (59). Arciniegas et al. (7) discuss this cell phenotype switch in the context of chronic pulmonary hypertension. Endothelial cells, when exposed in culture to TGF-β, transdifferentiate into cells that express smooth muscle cell markers and insulin-like growth factor II, thrombin, and its receptor PAR1; as well, both Notch and NF-κB activation (6–8, 43, 55) have been associated with EndMT. Given the established link between hypoxia, HIF-1α, and NF-κB, one can postulate that chronic hypoxia promotes EndMT in lung vessels.

_Angioobliterative Remodeling in Severe Pulmonary Hypertension_

The so-far discussed hypoxia-induced disease-mechanistic components inflammation, EndMT, and immune system modulation interact in models of CPHH, yet in animal models these mechanisms are insufficient to generate the lumen-obliterating pulmonary vasculopathy that characterizes severe forms of human PAH (93). We have used the term “angioobliterative” over the past years to distinguish between vessels with an open lumen and those that are closed such that there is no flow distal to the obliteration. Another implied meaning is “irreversibly closed,” in contrast to reversible muscularization of the pulmonary arteries after cessation of chronic hypoxic exposure. A second hit in addition to hypoxia is required. Knockout of the BMPR2 gene (44) or overexpression of IL-6 in mice (80), or induction of lung vascular endothelial cell apoptosis in rats together with chronic hypoxia (86), produce lumen obliteration in the lung vessels. BMPR2 protein expression is decreased in mice with CHPH but by itself is insufficient to cause complex lung lesion formation (14). Although it is still unknown which factors precipitate angioproliferative pulmonary lesions in individual patients with severe PAH (77), it is highly probable that the partial or total lumen closure of peripheral small lung vessels renders the tissue distal to the vascular obstruction ischemic (and perhaps even hypoxic when oxygen diffusion from the alveoli is insufficient), and that, together with vasoconstriction (82), in these microareas the biology of ischemia-reperfusion does apply.

If the pathobiology of these lesions can indeed be modeled by applying the concept of quasi-malignant cell growth (62), then, as in tumors, we need to consider a role of the regional effects of hypoxia-ischemia. Hypoxia is a key factor in tumor progression; it regulates apoptosis [selection of populations that are resistant to apoptosis (28)], cell proliferation, and angiogenesis, and it impairs DNA repair pathways (13) and induces autophagy (67) and the anaerobic metabolic switch (70). Although most patients with idiopathic PAH are not hypoxemic, unless they have developed an intracardial right-to-left shunt, lung tissue hypoxia-ischemia likely plays a role in the progressive worsening of the lung vascular disease. Another reason for lung tissue underperfusion and decreased peripheral lung tissue oxygenation is the pruning of the vascular tree, which can be demonstrated by pulmonary angiography in emphysema, in interstitial fibrosis, and in the angioobliterative forms of PAH. The coexistence of vessel loss and lumen-obliterating cell growth in the same lung remains mechanistically unexplained. In CHPH we find vessel pruning (disappearance) and muscularized arterioles. Meyrick and Reid (49, 65) in their ultrastructural studies described the pulmonary vascular remodeling in CHPH as a differentiation of pericytes and intermediate cell precursor cells into smooth muscle cells, a pathobiological concept that anticipated the discovery of vessel wall stem cells (10) and may complement the concept of EndMT.
degree of lung vessel closure in these latter models suffices to generate hypoxic/ischemic lung tissue regions distal to the occlusions is unknown, but likely. If so, tissue hypoxia could drive the continued maturation of lung vascular lesions that proceeds past the time of chronic hypoxia exposure of the animals (1).

**Hypoxia Induces Epigenetic Modifications**

In addition to the well-recognized, but still on a mechanistic level incompletely understood, genetic underpinnings of CHPH (11, 103), there is now an increasing interest in epigenetic control mechanisms of PAH (39). Polymorphisms in the EPAS1 or HIF-2α gene appear to account for the blunted polycythemic response of Tibetan high-altitude dwellers (11). Whether these polymorphisms also explain blunted pulmonary vascular responses in Tibetan highlanders is not clear. Both methylation and acetylation of histones determine the extent and degree of gene expression, and both are subject to dietary and environmental regulation. For example, a decreased expression of histone deacetylase-2 (HDAC2) has been shown in the lung tissue samples from smokers with chronic obstructive pulmonary disease (32). Mizuno et al. (52) demonstrated recently that HDAC inhibition decreases the expression of HIF-1α and causes emphysema. In contrast, chronic hypoxia increases lung tissue expression of HDAC 1, 2, 3, and 5 and HDAC inhibition ameliorates CHPH (18, 109). However, contrasting data have been published by Charron et al. (22) suggesting that activation of HIF-1α by hypoxia decreases HDAC2 levels; of interest is also the report by Hezroni et al. (30), which suggests that HDAC inhibition promotes the pluripotency of embryonic stem cells. Another example of epigenetic regulation is the copper-dependent expression and trans- activating activity of HIF-1α. Copper depletion decreases HIF-1α expression in the lung tissue and the expression of the HIF-1α target genes VEGF and LOX (51) and causes emphysema. However, animals raised on a Cu²⁺-depleted diet exposed to chronic hypoxia demonstrate the typically observed degree of pulmonary vascular muscularization (12). Thus HDAC inhibition, but not copper depletion, inhibits lung vascular muscularization in the rat CHPH model, indicating that HDAC dependently expressed genes and proteins participate in the remodeling responses of the lung vessels during chronic hypoxia. Endogenously generated HDAC inhibitors or environmental factors that inhibit HDAC activity would be expected to modify CHPH. Figure 5 shows also that HDAC

![Diagram of epigenetic modifications](Image)

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Fig. 5. In this schematic increased histone deacetylase (HDAC) expression is depicted upstream of HIF-1α, whereas HDAC inhibition leads to decreased HIF-1α expression, but increased expression of p53, both of which affect the muscularization of pulmonary arterioles during chronic hypoxia.

Although neither chronic hypoxia nor VEGFR blockade alone generates endovascular cell growth and obliteration of lung arterioles, the combination does. However, VEGFR blockade-induced lung vessel injury (endothelial cell apoptosis) does not require hypoxia as a second hit to cause obliteratorative lung vessel cell growth. The combination of VEGFR blockade and immunosufficiency (85) or the combination of VEGFR blockade and ovalbumin-induced lung inflammation (53) also cause angioobliterative PAH. Whether a certain

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Fig. 6. Lung histology and vascular lesions of rats treated with the HDAC inhibitor trichostatin A for 2 wk (daily intraperitoneal injection) following the development of severe angioobliterative pulmonary hypertension in the Sugen/chronic hypoxia model. Trichostatin A treatment did not affect the vascular lesions. Lumen occlusion, perivascular infiltrates, and emphysematous changes are present (trichrome stain).

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inhibition affects the lung tissue expression of the “guardian of the genome, p53.” This transcription factor controls cell growth and death and a large number of mutations have been associated with cancer cell growth. Mizuno et al. (50) have shown that p53 KO mice develop enhanced pulmonary vascular remodeling (muscularization) after chronic hypoxia; thus one can postulate that the HDAC inhibition-induced p53 expression contributes to the diminished muscularization in the HDAC inhibited CPH model (18). Remarkably, HDAC inhibition did not affect the angioblation that develops in the rat model of combined chronic hypoxia and VEGF receptor blockade (53), Fig. 6.

Synopsis

The experimental exploration of CPH initially focused on the role and mechanism of hypoxic pulmonary vascular constriction. Hypoxic vasocstriction can be investigated in lung arterial rings (33); however, the study of lung vascular remodeling in CPH requires the intact animal. The discoveries of HIF-1α and PGC-1α, a transcriptional regulator of mitochondrial metabolic programs (72), have opened the door to the understanding of the molecular mechanisms of hypoxic stress in normal and tumor tissues. Systemic hypoxic hypoxia evokes a complex system response that involves neuroendoctrine and innate immune system activation, is associated with the production of ROS, and is modulated by epigenetic phenomena. Many different cell types contribute to hypoxic vascular remodeling, and transitions between cell types (EndMT) have also been described. Although chronic hypoxia determines the adaptation to high altitude and chronic intermittent hypoxia leads to sleep apnea-related pulmonary hypertension, ischemic microregions of the lung are likely to exist in many chronic lung diseases in which pulmonary arterioles are lost or obliterated. In these areas, HIF- and PGC-1α-driven gene and protein expression is likely to play a role in the manifestation of “hypoxic inflammation.”

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

N.F.V. conception and design of research; N.F.V. performed experiments; N.F.V., S.M., and H.J.B. edited and revised manuscript; N.F.V., S.M., and H.J.B. prepared figures; N.F.V. and H.J.B. drafted manuscript; N.F.V., S.M., and H.J.B. reviewed manuscript.

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