Hypoxia-inducible factors (HIFs) are master regulators of oxygen homeostasis that match O$_2$ supply and demand for each of the 50 trillion cells in the adult human body. Cancer cells co-opt this homeostatic system to drive cancer progression. HIFs activate the transcription of thousands of genes that mediate angiogenesis, cancer stem cell specification, cell motility, epithelial-mesenchymal transition, extracellular matrix remodeling, glucose and lipid metabolism, immune evasion, invasion, and metastasis. In this Review, the mechanisms and consequences of HIF activation in cancer cells are presented. The current status and future prospects of small-molecule HIF inhibitors for use as cancer therapeutics are discussed.
Hypoxia-inducible factors: cancer progression and clinical translation

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Hypoxia-inducible factors and oxygen homeostasis

Oxygen homeostasis represents one of the most daunting and most essential challenges facing humans: to precisely supply, on a continuous basis, adequate O2 to each of the approximately 50 trillion cells in the adult human body to meet their metabolic demands for oxidative phosphorylation and several hundred other biochemical reactions that require O2 (1). Adding to the complexity of this challenge, cells throughout the body reside in tissue microenvironments with dramatically different O2 levels: airway epithelial cells are exposed to 21% O2, whereas in mouse thymus the median recorded partial pressure of oxygen (pO2) was 7.6 mmHg, which corresponds to approximately 1% O2 (2). Even within the same organ, tissue oxygenation varies tremendously: in the kidney, pO2 varies from 70 mmHg in the outer cortex to 10 mmHg in the inner medulla (3).

At the transcriptional level, the challenge to maintain oxygen homeostasis is met by the action of hypoxia-inducible factors (HIFs), which mediate reprogramming of each cell’s transcriptome in response to decreased O2 availability (i.e., hypoxia). HIFs modulate the balance between oxidative and glycolytic metabolism as a means of matching O2 demand with available supply (4, 5) and stimulate increased O2 delivery by activating the transcription of genes controlling erythropoiesis (6, 7) and angiogenesis (8, 9) to increase systemic and local O2 supply, respectively. Within any given cell subjected to hypoxia, the expression of hundreds to thousands of genes will be increased or decreased. For example, when SUM159 human breast cancer cells were transferred from a standard tissue culture incubator containing 95% air and 5% CO2 (i.e., 20% O2) to a chamber containing 1% O2 for 24 hours, expression levels of 1307 RNAs were significantly increased and of 817 RNAs were significantly decreased more than 1.5-fold in a HIF-dependent manner, i.e., these changes were not observed in cells in which HIF expression was silenced (10). Hypoxia-induced RNA expression is due to direct binding of HIFs to hypoxia response elements (HREs) in target genes, which contain the core HIF-binding site sequence 5′-(A/G)CGTG-3′ (11). In contrast, hypoxia-repressed RNA expression is indirectly mediated by the HIF-dependent activation of genes encoding microRNAs, transcriptional repressors, chromatin-modifying proteins, and proteins that modify or bind to RNA (12–15).

HIFs are heterodimeric proteins consisting of an O2-sensitive HIF-1α, HIF-2α, or HIF-3α subunit and a constitutively expressed HIF-1β subunit (also known as ARNT) (16). The mechanism by which changes in O2 availability are transduced to HIF-mediated changes in gene expression is remarkably straightforward: under normoxic conditions, an oxygen atom is inserted into a proline residue of HIF-1α, HIF-2α, or HIF-3α by one of three HIF prolyl hydroxylases (PHD1, PHD2, PHD3), and the von Hippel-Lindau (VHL) protein binds selectively to hydroxylated HIF-α subunits, targeting them for ubiquitination and proteasomal degradation, whereas under hypoxic conditions, hydroxylation is inhibited and non-hydroxylated HIF-α subunits accumulate, dimerize with HIF-1β, and bind to HREs in target genes to activate transcription (16). HIF transcriptional activity is further modulated by factor inhibiting HIF-1 (FIH-1), which hydroxylates an asparagine residue in the transactivation domain of HIF-α subunits, thereby blocking binding of the coactivator proteins p300 and CBP (17, 18). Thus, prolyl and asparaginyl hydroxylation of HIF-α subunits negatively regulates their half-life and transcriptional activity, respectively, in an O2-dependent manner.

The critical role of the HIF pathway in maintaining oxygen homeostasis is illustrated by the genetic condition known as familial erythrocytosis, in which affected individuals have...
increased red blood cell production. Affected individuals carry germline mutations in the gene encoding the erythropoietin receptor (EPOR), erythropoietin (EPO), HIF-2α (EPAS1), PHD2 (EGLN1), or VHL (6). Whereas mutations in the EPO or EPOR gene result in erythrocytosis only, mutations in EPAS1, EGLN1, or VHL increase HIF-1α and/or HIF-2α activity in every cell of the body and result in additional phenotypic manifestations, including pulmonary hypertension (19) and predisposition to thromboembolic events (20).

Familial erythrocytosis is a rare genetic disorder, whereas ischemic cardiovascular disease is one of the most common causes of mortality in the United States. The age-related impairment of vascular remodeling in response to ischemia that plays a critical role in the pathogenesis of this disorder is due in part to an age-related impairment of HIF activation (21). By contrast, increased HIF activity contributes to the pathogenesis of cancer, another major cause of mortality, as will be discussed in detail below.

Mechanisms of HIF activation in cancer
Many advanced human cancers contain regions of intratumoral hypoxia: the median P_{O2} in cancers of the breast, cervix, and head/neck is 10 mmHg (~1.4% O_2), with one-quarter of all measurements falling between 0 and 2.5 mmHg (22). Indeed, even preinvasive lesions, such as ductal carcinoma in situ of the breast, may contain regions of necrosis (23) in which O_2 availability is insufficient to maintain cell viability (24). In human breast cancers, measured diffusion distances for O_2 ranged from 70 μm at arterial inflow to 30 μm at venous outflow (3), meaning that O_2 rapidly becomes limiting as distance from the nearest blood vessel increases. Patients with cervical cancer, head/neck cancer, or soft-tissue sarcoma who have intratumoral P_{O2} less than 10 mmHg have significantly decreased survival (22). Intratumoral hypoxia is a stimulus for the induction of HIF-1α and HIF-2α protein expression, and increased expression of one or both of these proteins, as detected by immunohistochemical analysis of the diagnostic tumor biopsy, is associated with increased patient mortality in a wide range of solid cancers and leukemias (n = 101 studies; Supplemental Table 1; supplemental material available online with this article; https://doi.org/10.1172/JCI159839DS1). Whereas some cancers show a pattern of HIF-1α expression that is hypoxia-induced, in which cells furthest away from a blood vessel show the highest expression, in other cancers a homogeneous increase in HIF-1α expression is detected by immunohistochemistry, suggesting that an O_2-independent mechanism is responsible for increased expression (25).

The most dramatic example of O_2-independent HIF-1α and HIF-2α protein expression occurs in tumors associated with the von Hippel-Lindau syndrome, in which affected individuals are heterozygous for a germline loss-of-function mutation in the VHL tumor suppressor gene and the other allele is inactivated in the tumor tissue, leading to development of the clear-cell type of renal cell carcinoma (RCC), central nervous system and retinal hemangioblastoma, pancreatic neuroendocrine tumor, and other neoplasms (26). In these VHL-null tumors, cancer cells are strongly positive for HIF-1α and/or HIF-2α by immunohistochemistry (27, 28). In contrast to the partial loss-of-function mutations in VHL that cause erythrocytosis in the homozygous state but retain sufficient HIF binding activity to suppress tumor formation, heterozygosity for a VHL loss-of-function mutation is not sufficient to cause erythrocytosis, but loss of the second allele in the tumor results in VHL activity that is insufficient to suppress tumor formation. Loss of function for other tumor suppressors that frequently occurs in tumors due to somatic mutation or methylation, including p53 (29) and PTEN (30, 31), has also been reported to increase HIF-1α expression in one or more cancer types. Activation of receptor tyrosine kinases, such as the epidermal growth factor receptor (EGFR) and human epidermal growth factor receptor 2 (HER2), leads to increased mTOR activity and increased HIF-1α mRNA translation into protein in prostate (30) and breast (32) cancer, respectively. Many noncoding RNAs have been shown to dysregulate HIF-1α expression in cancer cells (33). Thus, genetic alterations and intratumoral hypoxia contribute in varying degree to the high levels of HIF-1α or HIF-2α that are observed in many human cancers.

Consequences of HIF activation in cancer
Whereas any given cancer cell will express only a subset of the large battery of HIF-regulated RNAs (>7000 identified to date), in aggregate these RNAs contribute to every critical aspect of cancer progression, including tumor vascularization, metabolic reprogramming, cell motility and invasion, and resistance to chemotherapy and radiation therapy (34–36). Most recently, HIFs have been shown to play major roles in cancer stem cell specification and immune evasion (33, 37, 38). Increased HIF activity in both cancer and stromal cells plays a critical role in immune evasion (39–42). The descriptions below are representative rather than comprehensive accounts of the thousands of HIF target genes expressed in human cancers. Metastasis is not listed as a separate category because it is dependent on all of the processes described below (43–45).

Vascularization. HIFs activate the expression of multiple angiogenic growth factors that contribute to intratumoral blood vessels, including vascular endothelial growth factor (VEGF), stromal-derived factor 1 (SDF1; also known as CXCL12), stem cell factor (also known as KIT ligand), placental growth factor, angiopoietin 2, angiopoietin-like 4, and other secreted factors that stimulate angiogenesis locally as well as serving to recruit bone marrow–derived angiogenic cells that participate in tumor vascularization (8, 21, 35, 46, 47). The expression of this large battery of genes provides a molecular basis for the frequent failure of anti-VEGF therapy to effectively block tumor angiogenesis and growth. Furthermore, to the extent that anti-VEGF therapy is successful in inhibiting angiogenesis, it increases intratumoral hypoxia, which may stimulate increased invasion and metastasis (48, 49) by mechanisms that will be described below. These observations suggest that safe and effective use of angiogenesis inhibitors may require coadministration of a HIF inhibitor.

Metabolic reprogramming. HIF-1 plays a critical role as master regulator of the balance between oxidative and glycolytic metabolism (50). It does so by activating the expression of over two dozen genes (Figure 1). Perhaps foremost among these are PDK1 (51, 52), encoding pyruvate dehydrogenase (PDH) kinase, which phosphorylates and inactivates the catalytic subunit of PDH, the enzyme...
that converts pyruvate to acetyl-CoA for entry into the tricarboxylic acid (TCA) cycle; and LDHA (11, 53), encoding lactate dehydrogenase, which converts pyruvate to lactate. Increased expression of PDK1 and LDHA shifts the balance of glucose metabolism to augment glycolysis and decrease mitochondrial respiration (51–53). Coordinate regulation of the genes encoding glucose transporters and glycolytic enzymes by HIF-1α (54) increases glucose flux through glycolysis as partial compensation for the reduced ATP yield compared with oxidative phosphorylation. Glycolytic flux is also stimulated by HIF-dependent expression of 6-phosphofructo-2-kinase/fructose-2,6-bisphosphatase-3 (PFKFB3), an enzyme that converts fructose-6-phosphate to fructose-1,6-bisphosphate, which is an allosteric inducer of phosphofructokinase (55).

Conventional wisdom held that cells switch from oxidative to glycolytic metabolism under hypoxic conditions in order to maintain ATP production. However, analysis of mouse embryo fibroblasts (MEFs) with knockout (KO) of HIF-1α led to a paradigm shift in our understanding of this metabolic adaptation. Unlike wild-type cells, HIF-1α–KO MEFs did not survive when cultured at 1% O2 for 3 to 4 days (51, 56). The HIF-1α–KO MEFs did not die as a result of ATP depletion: remarkably, ATP levels were higher in KO cells exposed to 1% O2 than in wild-type cells maintained at 20% O2. Clearly, the prevailing view that cells switched their metabolism because O2 was limiting for oxidative phosphorylation at 1% O2 was not correct. Instead, HIF-1α–KO MEFs died under long-term hypoxic conditions as a result of overwhelming levels of reactive oxygen species (ROS) (51, 56). HIF-1α–KO MEFs lost the ability to increase PDK1 expression in response to hypoxia, and their survival was rescued by forced expression of PDK1, which ameliorated ROS production under hypoxic conditions (51).

Life with O2 is a double-edged sword: When used as the terminal electron acceptor in respiration, it provides a mechanism for highly efficient ATP production. However, this process must be precisely modulated, because if the flow of electrons into the electron transport chain (ETC) at complex I is greater than the conversion of O2 to H2O at complex IV, electrons will spill out of complex I or III and combine with O2 non-catalytically to form superoxide anion. Under such circumstances, there are three possible adaptive responses: (a) decrease the flow of reducing equivalents from the TCA cycle to the ETC (e.g., by increasing PDK1 expression); (b) increase the activity of cytochrome c oxidase (complex IV); or (c) increase mitochondrial antioxidant capabilities to counteract the increased ROS production. In fact, all three of these strategies are employed by human cancer cells.

The most draconian measure employed to limit mitochondrial ROS production under hypoxic conditions is to eliminate mitochondria altogether, a process known as mitochondria-selective autophagy, thereby reducing oxidative metabolism of both glucose

Figure 1. HIF target genes that regulate glucose metabolism. HIF target genes that are induced under hypoxic conditions, leading to increased glycolysis and/or decreased oxidative phosphorylation, are shown in blue. Genes that promote oxidative metabolism are shown in red.
and fatty acids, which is mediated by HIF-dependent expression of the mitochondrial proteins BNIP3 (56) and BNIP3L (57). As described above for PDK1, the induction of BNIP3 expression in response to hypoxia is lost in HIF-1α- KO MEFs, and the cells can be rescued from ROS toxicity by forced expression of BNIP3 (56). Other HIF target genes that are expressed in order to maintain redox homeostasis include alternative subunits of ETC complex I (NDUFA4L2) and complex IV (COX4I2) that serve to either decrease the flow of electrons into the ETC at complex I (58) or increase the efficiency of electron transfer out of the ETC to O2 at complex IV (59), respectively. HIF-1-mediated expression of the microRNA miR-210 inhibits the expression of the iron-sulfur cluster scaffold proteins ISCU1 and ISCU2, which are required for complex I assembly, thereby decreasing mitochondrial respiration (60, 61). HIF-1 can also block the production of reducing equivalents in the TCA cycle by increased expression of SIAH2, which ubiquitinates the TCA cycle enzyme α-ketoglutarate dehydrogenase, targeting it for degradation (62). In breast cancer, the serine synthesis pathway and mitochondrial one-carbon metabolism are coordinately induced under hypoxic conditions to increase the generation of mitochondrial NADPH, which is required to maintain levels of reduced glutathione that are essential for countering the effects of increased ROS production (63). HIF-1 also controls glycogen synthesis and glycogenolysis, another metabolic cycle that plays a critical role in preventing toxic ROS production by cancer cells (64). Thus, HIFs function as master regulators for maintenance of ROS homeostasis in cancer cells under hypoxic conditions (Figure 1).

Epithelial–mesenchymal transition. A critical step in cancer progression is the epithelial–mesenchymal transition (EMT), in which cells lose the immobile epithelial phenotype characterized by a rigid cytoskeleton and extensive cell–cell interactions and take on a mesenchymal phenotype characterized by motility, which is enabled by a fluid cytoskeleton, loss of cell–cell interactions, and increased interactions with, and remodeling of, the extracellular matrix (ECM). Many HIF target genes contribute to each of these changes (43). In many cancers, EMT is controlled by a group of transcriptional repressors, including SNAIL, SLUG, TWIST, ZEB1, and ZEB2 (65), which downregulate the expression of E-cadherin and other epithelial cell–specific genes, and one or more of these repressors are HIF-regulated in many cancers (66–80). The HIF-dependent expression of many signaling proteins also promotes EMT (Supplemental Table 2).

Cell motility. Cell motility is triggered by members of the Rho family of GTPases, which mediate polymerization of actin stress fibers and serve as allosteric regulators of Rho-associated coiled-coil–forming kinase (ROCK) activity: GTP-loaded Rho binds (a) to ROCK and myosin phosphatase to stimulate phosphorylation and inhibit dephosphorylation of myosin light chain, respectively, leading to actin-myosin contraction; and (b) to LIM kinase to inhibit actin depolymerization (81–84). Hypoxia increases the motility of breast cancer cells, and this response is lost when expression of HIF-1α and HIF-2α is silenced (85). HIFs coordinately activate RHOA and ROCKI expression to stimulate the motility of hypoxic breast cancer cells (85). Cell motility requires the transmission of force through focal adhesions, which are correlated with cell velocity and regulated by focal adhesion kinase (FAK). Exposure of breast cancer cells to hypoxia induces FAK phosphorylation/activation and focal adhesion formation in a HIF-dependent manner (85). HIF-1 and HIF-2 also activate transcription of the ADAM12 gene, which encodes a protease that specifically clips the extracellular domain of heparin-bound EGF-like growth factor (HB-EGF), which binds to EGFR, leading to FAK phosphorylation; and ADAM12 knockdown in breast cancer cells is sufficient to block hypoxia-induced random motility, directed migration, and ECM invasion in vitro and metastasis from breast to lungs in vivo (86).

ECM remodeling. Cancer cells degrade and modify existing ECM, altering its biochemical and biophysical properties to facilitate tumor growth, tissue invasion, and distant metastasis (87–89). Cancer cells lay down highly cross-linked collagen fibers that serve as a stiff track for rapid cell migration, and HIFs mediate the expression of a wide range of collagens, including the fibrillar and fibril-like collagen I, V, XI, and XXVIII; network-forming/basement membrane collagens IV, VII, X, XV, and XVIII; filament-forming collagen VI; fibril-associated collagens IX, XIV, and XVI; transmembrane collagen XIII; and unclassified collagen XXVIII (10, 90–95); as well as collagen-modifying enzymes, including the lysyl oxidases LOX, LOXL2, and LOXL4; procollagen prolyl 4-hydroxylases P4HA1 and P4HA2; and procollagen-lysine, 2-oxoglutarate dioxygenases PLOD1 and PLOD2 (10, 93–103). In an orthotopic mouse model of breast cancer, metastasis from the mammary fat pad to the lungs was eliminated by knockdown of expression of P4HA1 or P4HA2 (97). Local tumor invasion and lung metastasis were also impaired by PLOD2 knockdown in breast cancer cells (99). The final stage of collagen fiber formation occurs following secretion of collagen fibrils into the extracellular space and is mediated by lysyl oxidases. These enzymes are not only secreted out of the cell but access the vasculature and travel to the lungs, liver, and other sites of metastasis, where they cross-link collagen and attract cancer cells also invade lymphatic vessels and colonize lymph nodes. Many of the HIF-regulated genes described above that affect cell motility, tissue invasion, and lung metastasis also affect metastasis of breast cancer cells to the regional lymph node. HIFs also promote the formation of breast cancer lymphatic vessels through expression of platelet-derived growth factor B (115).
Cancer stem cell specification. Cancer stem cells (CSCs) are defined by their self-renewal and tumor-initiating properties (116, 117). CSCs are specified by their expression of a group of transcription factors that were initially identified in embryonic stem cells as pluripotency factors: Krüppel-like factor 4 (KLF4), octamer-binding transcription factor 4 (OCT4), SRY-box 2 (SOX2), and NANOG (118–121). Although CSCs cannot give rise to every cell type found in the body (the definition of pluripotency), upon mitosis they do give rise to two different cell types: one transit-amplifying cancer cell, which can divide rapidly but only for a limited number of mitoses, and one CSC, such that the number of CSCs is never diminished. Because of the limited proliferative capacity of the bulk tumor cells, it is believed that only CSCs give rise to clinically relevant recurrent and/or metastatic tumors.

In breast cancer, exposure of cells to 1% O2 for 72 hours is sufficient to double or triple the percentage of CSCs within the body (the definition of pluripotency), upon mitosis they do give rise to two different cell types: one transit-amplifying cancer cell, which can divide rapidly but only for a limited number of mitoses, and one CSC, such that the number of CSCs is never diminished. Because of the limited proliferative capacity of the bulk tumor cells, it is believed that only CSCs give rise to clinically relevant recurrent and/or metastatic tumors.
Immune evasion. In order for a cancer cell to form a metastatic focus, it must have CSC properties, and it must be able to evade killing by cells of the adaptive and innate immune systems. Cancer cells reprogram the tumor immune microenvironment to shift the balance from antitumor immunity to immunosuppression (141). Cytotoxic CD8+ T cells and natural killer (NK) cells are the major agents of adaptive and innate antitumor immunity, respectively. Cancer cells inhibit the activity of CD8+ T cells and stimulate the activity of regulatory T cells in order to evade killing by the adaptive immune system (Figure 3). Cancer cells also inhibit the activity of NK cells and recruit tumor-associated macrophages (TAMs) and myeloid-derived suppressor cells (MDSCs), components of the innate immune system that promote immunosuppression (141). A growing number of HIF target genes mediate this reprogramming of the tumor immune microenvironment (37–42). It is striking that many HIF target genes that mediate immune evasion also play important roles in mediating other critical aspects of cancer progression, such as angiogenesis, CSC specification, and metabolism (Supplemental Table 3).

Cancer cells are known to take up large quantities of glucose through the glucose transporter GLUT1 (encoded by the SLC2A1 gene) and produce lactic acid (through the activity of LDHA and PKD1), either as a response to intratumoral hypoxia or driven in an O2-independent manner by genetic alterations (which is known as the Warburg phenomenon), and the lactate and H+ ions generated by LDHA are pumped out of the cancer cell by the monocarboxylate transporter MCT4 (encoded by the SLC16A3 gene), the carnitonic anhydrase CA9, and the sodium hydrogen exchanger NHE1 (encoded by the SLC9A1 gene) (142–144). The resulting decrease in extracellular glucose and increase in extracellular lactate and H+ are all immunosuppressive (145–148). Thus, one of the classical features of advanced cancers, glycolytic metabolism, which previously was interpreted solely in terms of cancer cell energetics and proliferation, is now appreciated to play a critical role in the establishment of an immunosuppressive tumor microenvironment.

Hypoxia-induced expression of PDL1 (encoded by the CD274 gene) and production of adenosine by cancer cells through the activity of CD73 (encoded by the NT5E gene) lead to immunosuppression (Supplemental Table 3) via binding to cognate receptors (PD-1 and adenosine receptor 2A, respectively) on NK and CD8+ T cells that results in exhaustion or apoptosis. However, the direct effect of hypoxia on T cells is less clear. Hypoxia has been reported to induce the expression of markers of T cell exhaustion, such as TIM3 and LAG3, as well as costimulatory receptors, such as 4-1BB, GITR, and OX40 (149). CD8+ T cells with increased HIF activity due to VHL conditional KO also express markers of tissue-resident memory T cells (CD69 and CD103) and have increased antitumor activity (150). However, it appears that the net effect of hypoxia in most tumors is immunosuppression, and administration of supplemental O2 (151) or a drug that is selectively toxic to hypoxic cells (152) is sufficient to increase the number of intratumoral T cells and the response to immunotherapy.

Women with TNBC are not eligible for targeted therapies and are treated with cytotoxic chemotherapy that often provides only a brief remission before recurrence, often in the form of metastatic disease. TNBC cells that survive cytotoxic chemotherapy, such as carboplatin or paclitaxel, stimulate an immunosuppressive tumor microenvironment with increased numbers of MDSCs and TAMs, decreased expression of NK and CD8+ T cells, and increased HIF activity that drives expression of CD73, PD-L1, and CD47, the latter of which protects cancer cells from phagocytosis by macrophages (153). Cytotoxic chemotherapy also induces HIF-dependent CSC specification (124), resulting in tumor-initiating cells that can evade both adaptive and innate immunity. Coadministration of the HIF inhibitor acriflavine with paclitaxel or carboplatin blocks the induction of an immunosuppressive tumor microenvironment (153). In melanoma and breast cancer cells, hypoxia induces HIF-dependent expression of BIRC2, which inhibits expression of CXCL9, thereby blocking recruitment of NK and CD8+ T cells to the tumor, leading to increased tumor growth and resistance to anti–PD-1 therapy (154).

Intratumoral hypoxia affects not only cancer cells but also the stromal cells within the tumor, most notably immune cells (39, 40). In contrast to the large body of data presented above indicating that HIF activity in cancer cells drives immune evasion, studies focused on the conditional KO of HIFs in immune cell populations have reported that HIFs play important cell-autonomous roles in CD4+ and CD8+ effector T cells, MDSCs, TAMs, Th17 cells, and NK cells; however, many of these studies have revealed distinct roles for HIF-1α versus HIF-2α, and distinct effects of loss of function in the same immune cell type in different tumor models (39). In recent studies using mouse models of breast cancer described above (153) and hepatocellular carcinoma described below, we have found that the net effect of pharmacologic inhibition of HIFs is to significantly increase antitumor immunity.

Targeting HIFs for cancer therapy

A large number of chemical compounds have been shown to inhibit HIF activity in cancer cell lines (155). HIF inhibitors that have shown antitumor activity in mouse tumor models include acriflavine (47), digoxin (106), echinomycin (156), the HSP90 inhibitors 17-allylamino-geldanamycin (157) and ganetespib (158), 2-methoxyestradiol (159), PX-478 (160), and YC-1 (161). Many of these compounds are too toxic for use in humans as HIF inhibitors or have failed in clinical trials. Two compounds, PT2385 and PT2399, were shown to bind directly and selectively to HIF-2α and block its dimerization with HIF-1β, thereby inhibiting the expression of HIF-2 target genes and the growth of HIF-2-dependent...
RCC xenografts (162–164). Both compounds showed safety and activity against advanced RCC in phase I trials (165, 166). PT2399 (belzutifan) showed efficacy against RCC and other tumors in patients with von Hippel-Lindau syndrome in a phase III trial (140) and was recently approved by the FDA for this indication (167). RCC and other tumors in von Hippel-Lindau syndrome patients are outliers in that disease progression is often associated with loss of HIF-1α expression, which may be due in part to selection against HIF-1α-dependent inhibition of MYC activity (168). This stands in contrast to most cancer types, in which increased HIF-1α expression is associated with disease progression and patient mortality (Supplemental Table 1). The development of belzutifan is a major advance in the treatment of RCC, but preclinical studies revealed that some RCC cell line–derived tumors and patient–derived xenografts showed resistance to HIF-2 inhibitors (162, 164). One mouse model of RCC that was resistant to PT2385 responded to treatment with acrilavine (169), which binds to HIF-2α (and HIF-1α) at a site different from that of PT2385 (47, 170). There are multiple registrations for clinical trials involving belzutifan at ClinicalTrials.gov (Supplemental Table 4).

Hepatocellular carcinoma (HCC) is the most rapidly growing cause of cancer mortality in the United States with a 5-year survival rate of less than 12% (171). Nivolumab, an anti–PD-1 antibody, received FDA approval based on phase II clinical trial data, but the phase III trial did not meet its primary endpoint, and a phase III trial of pembrolizumab, another anti–PD-1 antibody, also failed as second-line therapy (172, 173). Liver cancers are characterized by severe intratumoral hypoxia with a median pO₂ of 6 mmHg (0.9% O₂) compared with 30 mmHg in normal liver tissue (174). Phosphatidylinositol-3-kinase and AKT signaling also contribute to increased HIF activity in HCC (175). Increased HIF-1α expression in the HCC diagnostic biopsy is associated with decreased disease-free and overall survival (176). In nude mice bearing Hep3B human HCC xenografts, treatment with 32-134D, a novel HIF inhibitor, decreased the expression of HIF-1 and HIF-2 target genes and decreased tumor vascularization (177). In immunocompetent mice bearing Hepa1-6 mouse HCC tumors, combined treatment with 32-134D and anti–PD-1 antibody resulted in tumor eradication in 67% of the mice compared with 25% of the mice treated with anti–PD-1 alone (177). Treatment with 32-134D resulted in a significant increase in intratumoral NK and CD8+ T cells and a significant decrease in intratumoral MDSCs and TAMs, which were associated with increased expression of CXCL9 and CXCL10, the key chemokines for NK and T cell recruitment (177).

Whereas treatment of humans or mice with PT2385 or PT2399/belzutifan caused anemia due to inhibition of erythropoietin expression (140, 165, 166), treatment of mice with 32-134D did not affect plasma erythropoietin levels or red blood cell indices and had no effect on appearance, behavior, or body weight (177). HIFs play critical roles in vascular remodeling in response to ischemic cardiovascular disease (8), and treatment of mice with the HIF inhibitor 2-methoxyestradiol inhibited recovery of blood flow and increased tissue injury after femoral artery ligation (21). It is therefore possible that HIF inhibitors might have adverse effects in patients with severe coronary or peripheral artery disease. However, the observation that 32-134D does not affect blood erythropoietin levels (177) suggests that it might have a selective inhibitory effect in HCC cells. Clinical trials will determine whether a therapeutic window exists for the safe and efficacious use of combined HIF-1/HIF-2 inhibitors for cancer therapy. A recent review summarized the experimental data supporting the concept that HIF-1 and HIF-2 play complementary roles in many cancers and that targeting both HIF-1 and HIF-2 for inhibition will provide greater therapeutic benefit than targeting either one of them alone (39). Given the requirement for HIF expression in many cancer types, the extraordinarily high levels of expression in comparison with normal tissues, and the limited evidence of toxicity in mouse models, it seems likely that HIF inhibitors will be valuable new weapons with which to fight cancer.

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1. Raymond J, Segre D. The effect of oxygen on biochemical networks and the evolution of complex life. Science. 2006;315(5816):1764-1767.
2. Braun RD, et al. Comparison of tumor and normal tissue oxygen tension measurements using OxyLite or microelectrodes in rodents. Am J Physiol Heart Circ Physiol. 2001;280(6):2533-2544.
3. Vaupe1 P, et al. Oxygenation status of malignant tumors vs. normal tissues: critical evaluation and updated data source based on direct measurements with pO₂ microsensors. Appl Magn Reson. 2021;52:1451-1479.
4. Semenza GL. HIF-1 mediates metabolic responses to intratumoral hypoxia and oncogenic mutations. J Clin Invest. 2013;123(9):3664-3671.
5. Kierans SJ, Taylor CT. Regulation of glycolysis by the hypoxia-inducible factor (HIF): implications for cellular physiology. J Physiol. 2021;599(1):23–37.
6. Semenza GL. Breakthrough science: hypoxia-inducible factors, oxygen sensing, and disorders of hematopoiesis. Blood. 2022;139(16):2441-2449.
7. Watts D, et al. Hypoxia pathway proteins are master regulators of erythropoiesis. Int J Mol Sci. 2020;21(2):8131.
8. Rey-S, Semenza GL. Hypoxia-inducible factor–1-dependent mechanisms of vascularization and vascular remodeling. Cardiovasc Res. 2010;86(2):256–242.
9. Rodriguez D, et al. Hypoxia pathway proteins and their impact on the blood vasculature. Int J Mol Sci. 2021;22(17):9191.
10. Wang Y, et al. Histone citrullination by PADI4 is required for HIF-dependent transcriptional responses to hypoxia and tumor vascularization. Sci Adv. 2021;7(35):eabe5771.
11. Semenza GL, et al. Hypoxia response elements in the aldolase A, enolase 1, and lactate dehydrogenase A gene promoters contain essential binding sites for hypoxia-inducible factor 1. J Biol Chem. 1996;271(15):32529–32537.
12. Camps C, et al. Integrated analysis of microRNA and mRNA expression and association with HIF binding reveals the complexity of microRNA expression regulation under hypoxia. Mol Cancer. 2014;13:28.
13. Cavadas MA, et al. The regulation of transcriptional repression in hypoxia. Exp Cell Res. 2017;356(2):173–181.
14. Schödel J, et al. High-resolution genome-wide mapping of HIF-binding sites by ChiP-seq. Blood. 2011;117(23):e207–e217.
15. Zhang C, et al. Hypoxia induces the breast cancer stem cell phenotype by HIF-dependent and ALKBN5-mediated mTOR-demethylation. Proc Natl Acad Sci U S A. 2016;113(14):2047-2056.

16. Semenza GL. The genomics and genetics of oxygen homeostasis. Annu Rev Genomics Hum Genet. 2020;21:183-204.

17. Lando D, et al. FIH-1 is an asparaginyl hydroxylase enzyme that regulates the transcriptional activity of hypoxia-inducible factor. Genes Dev. 2002;16(12):1466-1471.

18. Mahon PC, et al. FIH-1: a novel protein that interacts with HIF-1α and VHL to mediate repression of HIF-1 transcriptional activity. Genes Dev. 2001;15(20):2675-2686.

19. Gale DP, et al. Autosomal dominant erythrocytosis due to up-regulated hypoxia sensitivity. J Clin Invest. 1955;9(4):539-549.

20. Gordeuk VR, et al. Thrombotic risk in congenital erythrocytosis. J Clin Invest. 2002;112(3):519-521.

21. Krieg M, et al. Up-regulation of hypoxia-inducible factor. Genes Dev. 2000;14(4):391-396.

22. Laughner E, et al. HER2 (neu) signaling increases the rate of hypoxia-inducible factor 1α (HIF-1α) synthesis: novel mechanism for HIF-1-mediated vascular endothelial growth factor expression. Mol Cell Biol. 2001;21(12):3995-4004.

23. Zhang C, et al. Role of hypoxia-inducible factor-1 in cancer stem cells. Mol Med Rep. 2021;23(1):17.

24. Bao MH, Wong CC. Hypoxia, metabolic reprogramming, and drug resistance in liver cancer. Cells. 2021;10(7):1715.

25. De Heer EC, et al. HIFs, angiogenesis and metabolism: elusive enemies in breast cancer. J Clin Invest. 2020;330(10):5074-5087.

26. Schito L, Semenza GL. Hypoxia-inducible factors: master regulators of cancer progression. Trends Cancer. 2016;2(12):758-770.

27. Krieg M, et al. Up-regulation of hypoxia-inducible factor. Antioxid Redox Signal. 2007;9(8):1221-1235.

28. Zhong H, et al. Overexpression of hypoxia-inducible factor 1α induces the recruitment of mitochondrial oxygen consumption. Cell Metab. 2016;33(3):187-197.

29. Le A, et al. Inhibition of lactate dehydrogenase A induces oxidative stress and inhibits tumor progression. Proc Natl Acad Sci U S A. 2010;107(5):2037-2042.

30. Iyer NV, et al. Cellular and developmental control of O2 homeostasis by hypoxia-inducible factor 1α. Genes Dev. 1998;12(2):149-162.

31. Minchenko A, et al. Hypoxia-inducible factor-1-mediated expression of the 6-phosphofructo-2-kinase/fructose-2,6-bisphosphatase-3 (PFKFB3) gene: its possible role in the Warburg effect. J Biol Chem. 2002;277(8):6183-6187.

32. Zhang Y, et al. Mitochondrial autophagy is an HIF-1-dependent adaptive metabolic response to hypoxia. J Biol Chem. 2008;283(16):10892-10903.

33. Bellot G, et al. Hypoxia-induced autophagy is mediated through hypoxia-inducible factor induction of BNIP3 and BNIP3L via their BH3 domains. Mol Cell Biol. 2009;29(10):2570-2581.

34. Tello D, et al. Induction of mitochondrial NDUFA4L2 protein by HIF-1α decreases oxygen consumption by inhibiting complex 1 activity. Cell Metab. 2011;14(6):768-779.

35. Fukuda R, et al. HIF-1 regulates cytochrome oxidase subunits to optimize efficiency of respiration in hypoxic cells. Cell. 2007;129(1):111-122.

36. Chan SY, et al. MicroRNA-210 controls mitochondrial metabolism during hypoxia by repressing the iron-sulfur cluster assembly protein ISCU1/2. Cell Metab. 2009;10(4):273-284.

37. Favaro E, et al. MicroRNA-210 regulates mitochondrial free radical response to hypoxia and Krebs cycle in cancer cells by targeting iron sulfur cluster protein ISCU. Proc Natl Acad Sci U S A. 2010;107(5):e10345.

38. Sun RC, Denko NC. Hypoxic regulation of glutamine metabolism through HIF-1 and SIAH2 supports lipid synthesis that is necessary for tumor growth. Cell Metab. 2014;19(2):285-292.

39. Samanta D, et al. PHGDH expression is required for mitochondrial redox homeostasis, breast cancer stem cell maintenance, and lung metastasis. Cancer Res. 2016;76(15):4340-4342.

40. Favaro E, et al. Glucose utilization via glycogen phosphorylase sustains proliferation and prevents premature senescence in cancer cells. Cell Metab. 2012;16(6):751-764.

41. Zeisberg M, Neilson EG. Biomarkers for epithelial-mesenchymal transitions. J Clin Invest. 2009;119(6):1429-1437.

42. Chen S, et al. Hypoxia induces TWIST-activated epithelial-mesenchymal transition and proliferation of pancreatic cancer cells in vitro and in nude mice. Cancer Lett. 2016;383(1):73-84.

43. Chen Z, et al. Overexpression of Trp53 promotes tumor metastasis via the HIF-1α-Twist signaling pathway in colon cancer. Clin Sci (Lond). 2017;131(19):2439-2450.

44. Cheng JC, et al. Hypoxia-inducible factor 1α mediates epidermal growth factor-induced down-regulation of E-cadherin expression and cell invasion in human ovarian cancer cells. Cancer Lett. 2013;329(2):197-206.

45. Depner C, et al. Ephrin B2 repression through ZEB2 mediates tumor invasion and anti-angiogenic resistance. Nat Commun. 2016;7:12329.

46. Gao H, et al. SOX2 promotes epithelial to mesenchymal transition by activating HIF-1α, which enhances tumorigenicity in vitro and in vivo. Cancer Res. 2011;71(12):4335-4344.
enchymal transition of esophageal squamous cells by modulating Slug expression through the activation of STAT3/HIF-1α signaling. Int J Mol Sci. 2015;16(9):21643–21657.
71. Gort EH, et al. The TWIST1 oncogene is a direct target of hypoxia-inducible factor 2a. Oncogene. 2008;27(11):1501–1510.
72. Joseph JV, et al. Hypoxia enhances migration and invasion in glioblastoma by promoting a mesenchymal shift mediated by HIF-1α-ZEB1 axis. Cancer Lett. 2015;359(1):107–116.
73. Krishnamachary B, et al. Hypoxia-inducible factor-1-dependent repression of E-cadherin in von Hippel-Lindau tumor suppressor-null renal cell carcinoma mediated by TCF3, ZFHX1A, and ZFHX1B. Cancer Res. 2006;66(5):2725–2731.
74. Liu KH, et al. Hypoxia stimulates the epithelial-to-mesenchymal transition in lung cancer cells through accumulation of nuclear β-catenin. Anticancer Res. 2018;38(13):6299–6308.
75. Liu Y, et al. HIFs enhance the migratory and neoplastic capacities of hepatocellular carcinoma cells by promoting EMT. Tumour Biol. 2014;35(8):8103–8114.
76. Luo D, et al. Mouse snail is a target gene for HIF. Mol Cancer Res. 2011;9(2):235–245.
77. Park JB, et al. Neddylation blockade induces HIF-1α driven cancer cell migration via upregulation of ZEB1. Sci Rep. 2020;10(1):38210.
78. Yang S, et al. HIF-1α induces the epithelial-mesenchymal transition in gastric cancer cell lines through the Snail pathway. Oncotarget. 2017;8(6):9535–9545.
79. Yang MH, et al. Direct regulation of twist1 in colorectal cancer. Oncotarget. 2016;7(37):55111–55120.
80. Erler JT, et al. Lysyl oxidase is essential for hypoxia-induced metastasis. Nature. 2006;440(7088):1222–1226.
81. Gilkes DM, et al. Hypoxia-inducible factor 1 (HIF-1) promotes extracellular matrix remodeling under hypoxic conditions by inducing PAH1, PAH2, and PLD2 expression in fibroblasts. J Biol Chem. 2013;288(15):10819–10829.
82. Gilkes DM, et al. Collagen prolyl hydroxylases are essential for breast cancer metastasis. Cancer Res. 2013;73(11):3285–3296.
83. Gilkes DM, et al. Hypoxia-inducible factor 1 (HIF-1) promotes extracellular matrix remodeling under hypoxic conditions by inducing PAH1, PAH2, and PLD2 expression in fibroblasts. J Biol Chem. 2013;288(15):10819–10829.
84. Gilkes DM, et al. Procollagen lysyl hydroxylase 2 is essential for hypoxia-induced breast cancer metastasis. Mol Cancer Res. 2013;11(5):456–466.
85. Hoffbauer KH, et al. Oxygen tension regulates the expression of a group of procollagen hydroxylases. Eur J Biochem. 2003;270(22):4519–4522.
86. Schietke R, et al. The lysyl oxidases LOX and LOXL2 are necessary and sufficient to repress E-cadherin in hypoxia: insights into cellular transformation processes mediated by HIF-1. J Biol Chem. 2010;285(9):6658–6669.
87. Takahashi Y, et al. Hypoxic induction of prolyl 4-hydroxylase alpha (I) in cultured cells. J Biol Chem. 2000;275(19):14139–14146.
88. Wong CC, et al. Hypoxia-inducible factor 1α is a master regulator of breast cancer metastatic niche formation. Proc Natl Acad Sci U S A. 2011;108(39):16369–16374.
89. Erler JT, et al. Hypoxia-induced lysyl oxidase is a critical mediator of bone marrow cell recruitment to form the premetastatic niche. Cancer Cell. 2009;15(1):35–44.
90. Kaplan RN, et al. VEGFRI-positive hematopoietic bone marrow progenitors initiate the pre-metastatic niche. Nature. 2005;438(7069):820–827.
91. Zhang X, et al. Hypoxia and other cardi-ac glycosides inhibit HIF-1α synthesis and block tumor growth. Proc Natl Acad Sci U S A. 2008;105(50):19579–19586.
92. Wong CC, et al. Inhibitors of hypoxia-inducible factor 1 block breast cancer metastatic niche formation and lung metastasis. J Mol Med (Berl). 2012;90(7):803–815.
93. Cowden Dahl KD, et al. Hypoxia-inducible factor regulates αβ integrin cell surface expression. Mol Biol Cell. 2005;16(4):1901–1912.
127. Lan J, et al. Hypoxia-inducible factor 1-dependent expression of adenosine receptor 2B promotes breast cancer stem cell enrichment. Proc Natl Acad Sci U S A. 2018;115(41):E9640–E9648.

128. Lu H, et al. Chemotherapy triggers HIF-1-dependent glutathione synthesis and copper chelation that induces the breast cancer stem cell phenotype. Proc Natl Acad Sci U S A. 2015;112(33):E4600–E4609.

129. Lu H, et al. Chemotherapy-induced Ca2+ release stimulates breast cancer stem cell enrichment. Cell Rep. 2017;18(8):1946-1957.

130. Lu H, et al. Chemotherapy-induced S100A10 recruits KDM6A to facilitate OCT4-mediated breast cancer stemness. J Clin Invest. 2020;130(9):4607–4623.

131. Lu H, et al. Reciprocal regulation of DUSP9 and DUSP16 expression by HIF-1 controls ERK and p38 MAP kinase activity and mediates chemotherapymediated breast cancer stem cell enrichment. Cancer Res. 2018;78(15):4319–4202.

132. Zhang C, et al. Hypoxia-inducible factors regulate pluripotency factor expression by ZNF217- and ALKBH5-mediated modulation of RNA methylation in breast cancer cells. Oncotarget. 2016;7(40):64527–64542.

133. Zhang H, et al. HIF-1-regulated expression of calreticulin promotes breast tumorigenesis and progression through Wnt/b-catenin pathway activation. Proc Natl Acad Sci U S A. 2021;118(44):e2109441148.

134. Lu H, et al. HIF-1 recruits NANO as a coactivator for TERT gene transcription in hypoxic breast cancer stem cells. Cell Rep. 2021;36(13):109757.

135. Shary JW, Wright SE. Telomeres and telomerase enzyme inhibitor of hypoxia-inducible factor-1α DNA-binding activity. Cancer Cell. 2003;3(4):374–381.

136. Zhang H, et al. HIF-1 regulates CD47 expression in breast cancer patients that initiates metastasis in a xenograft assay. Nat Biotechnol. 2013;31(6):539–544.

137. Krishnamachary B, et al. Hypoxia regulates HIF-1α-dependent and HSP90 inhibitor-induced degradation of p38 MAP kinase activity and mediates chemo- therapy-induced breast cancer stem cell enrichment. Proc Natl Acad Sci U S A. 2020;117(15):9409–9419.

138. Pennacchietti S, et al. Hypoxia promotes invasive growth and angiogenesis by disrupting microtubules and dysregulating HIF. Cancer Cell. 2003;3(4):363–375.

139. Welsh S, et al. Antitumor activity and pharmacodynamic properties of PX-478, an inhibitor of hypoxia-inducible factor-1α. Mol Cancer Ther. 2004;3(3):233–244.

140. Yeo EJ, et al. YC-1: a potential anticancer drug targeting hypoxia-inducible factor 1α. Nat Cancer Inst. 2003;95(7):516–525.

141. Liu YV, et al. RACK1 competes with HSP90 for recruitment of CD47+/CD73+/PDL1+ immune evasive breast cancer cells. Proc Natl Acad Sci U S A. 2013;110(19):7879–7884.

142. Baccelli I, et al. Identification of a population of patients that initiates metastasis in a xenograft model of triple negative breast cancer. PLoS One. 2012;7(8):e44078.

143. Parks SK, et al. Disrupting proton dynamics and energy metabolism for cancer therapy. Nat Rev Cancer. 2013;13(9):611–623.

144. Semenza GL. HIF-1 mediates the Warburg effect in clear cell renal carcinoma. J Bioenerg Biomembr. 2007;39(3):231–234.

145. Brand A, et al. LDHA-associated lactic acid production blunts tumor immunosurveillance by T and NK cells. Cell Metab. 2016;24(5):657–671.

146. Chang CH, et al. Metabolic competition in the tumor microenvironment is a driver of cancer progression. Cell. 2015;162(6):1229–1241.

147. Fischer K, et al. Inhibitory effect of tumor cell-derived lactic acid on human T cells. Blood. 2007;109(9):3812–3819.

148. Ottensmeier CH, et al. Upregulated glucose metabolism correlates inversely with CD8+ T-cell infiltration and survival in squamous cell carcinoma. Cancer Res. 2016;76(14):4316–4348.

149. Banrud N, et al. Hypoxia supports differentiation of terminally exhausted T cells. Front Immunol. 2021;12:660944.

150. Liakakos T, et al. Hypoxia-inducible factor activity promotes antitumor effector function and tissue residency by CD8+ T cells. J Clin Invest. 2021;131(7):e143729.

151. Hatfield SM, Sitkowski MV. Anti-hypoxic oxygenation agents with respiratory hyperoxia to improve cancer immunotherapy. J Clin Invest. 2020;130(11):5629–5637.

152. Jayaprakash P, et al. Targeted hypoxia reduction restores T cell infiltration and sensitizes prostate cancer to immunotherapy. J Clin Invest. 2018;128(12):5137–5149.

153. Samanta D, et al. Chemotherapy induces enrichment of CD47+/CD73+/PDL1+ immune evasive triple-negative breast cancer cells. Proc Natl Acad Sci U S A. 2018;115(16):E1239–E1248.

154. Samanta D, et al. BIR2 expression impairs anti-cancer immunity and immunotherapy efficacy. Cell Rep. 2020;32(8):108073.

155. Semenza GL. Pharmacologic targeting of hypoxia-inducible factors. Annu Rev Pharmacol Toxicol. 2019;59:379–403.

156. Kong D, et al. Echinomycin, a small-molecule inhibitor of hypoxia-inducible factor-1α DNA-binding activity. Cancer Res. 2005;65(19):9047–9055.

157. Liu YV, et al. RACK1 competes with HSP90 for recruitment of CD47+/CD73+/PDL1+ immune evasive triple-negative breast cancer cells. Proc Natl Acad Sci U S A. 2018;115(16):E1239–E1248.

158. Xiang L, et al. LY-294002 enhances the chemosensitivity of liver cancer to oxaliplatin by blocking PI3K/AKT/HIF-1α the PI3K/AKT/HIF-1α pathway. PLoS One. 2012;7(8):e44078.

159. Macchiarelli R, et al. Hypoxia promotes invasive growth by transcriptional activation of the met protooncogene. Cancer Cell. 2003;3(4):374–381.

160. Zhang H, et al. HIF-1 regulates CD47 expression in breast cancer cells to promote evasion of phagocytosis and maintenance of cancer stem cells. Proc Natl Acad Sci U S A. 2015;112(45):E6215–E6223.

161. Yeo EJ, et al. Chemotherapy-induced Ca2+ release stimulates breast cancer stem cell enrichment. Cell Rep. 2017;18(8):1946-1957.

162. Salzman S, et al. HIF inhibitor 32-134D eradicates murine hepatocellular carcinoma in combination with anti-PDI therapy. J Clin Invest. 2022;132(9):e156774.