Preclinical Characterization of Vadadustat (AKB-6548), an Oral Small Molecule Hypoxia-Inducible Factor Prolyl-4-Hydroxylase Inhibitor, for the Potential Treatment of Renal Anemia

Anna Zuk, Zhihai Si, Sally Loi, Santhosh Bommegowda, Debie Hoivik, Sanjay Danthi, Gyongyi Molnar, Vilmos Csizmadia, and Michael Rabinowitz


Received January 25, 2022; accepted July 5, 2022

ABSTRACT
Pharmacological inhibition of prolyl-4-hydroxylase domain (PHD) enzymes stabilizes hypoxia-inducible factors (HIFs), transcription factors that activate target genes that, among others, increase erythropoietin (EPO) synthesis, resulting in the production of new red blood cells (RBCs). Herein, we summarize the preclinical characteristics of the small molecule HIF prolyl-4-hydroxylase inhibitor vadadustat (AKB-6548), which is in development for the treatment of anemia in patients with chronic kidney disease (CKD). Vadadustat inhibits the enzyme activity of all three human PHD isoforms, PHD1, PHD2, and PHD3, with similar low nanomolar inhibitory constant values. PHD enzyme inhibition by vadadustat is competitive with endogenous cofactor 2-oxoglutarate and is insensitive to free iron concentration. In the human hematopoietic cell line (Hep 3B) and human umbilical vein endothelial cells, PHD inhibition by vadadustat leads to the time- and concentration-dependent stabilization of HIF-1α and HIF-2α. In Hep 3B cells, this in turn results in the synthesis and secretion of EPO; vascular endothelial growth factor is not measured at detectable levels. A single oral dose of vadadustat in rats potently increases circulating levels of EPO, and daily oral dosing for 14 days increases RBC indices in healthy rats and in the 5/6 nephrectomy model of CKD. In mice and dogs, once-daily repeat oral dosing increases hemoglobin and hematocrit. Vadadustat has a relatively short half-life in all nonclinical species evaluated and does not accumulate when administered as a single bolus dose (oral or intravenous) or upon repeat oral dosing. The pharmacological profile of vadadustat supports continued development for treatment of renal anemia.

SIGNIFICANCE STATEMENT
Vadadustat (AKB-6548) is an orally bioavailable small molecule prolyl-4-hydroxylase inhibitor in development for anemia of chronic kidney disease. It is an equipotent inhibitor of the three human prolyl-4-hydroxylase domain isoforms, which activates erythropoiesis through stabilization of hypoxia-inducible factor (HIF)-1α and HIF-2α, increasing production of erythropoietin, without detectable stimulation of vascular endothelial growth factor.

Introduction
Chronic kidney disease (CKD) is a major source of morbidity and mortality worldwide and costs the healthcare industry billions of dollars annually. In addition to the risk of heart disease, stroke, and early death, patients with CKD face higher risks of developing anemia, a result of failing kidney function (US Department of Health and Human Services, 2021). Kidneys are highly metabolically active organs requiring energy to remove waste from the blood, reabsorb nutrients, regulate the balance of electrolytes and fluid, maintain acid-base balance, and excrete waste products. Additionally, kidneys produce EPO, a hormone that stimulates the production of red blood cells (RBCs). The kidney is responsible for producing as much as 90% of the body’s EPO; therefore, a decrease in kidney function results in decreased production of EPO, leading to anemia.

Preclinical Characterization of Vadadustat (AKB-6548), an Oral Small Molecule Hypoxia-Inducible Factor Prolyl-4-Hydroxylase Inhibitor, for the Potential Treatment of Renal Anemia

Anna Zuk, Zhihai Si, Sally Loi, Santhosh Bommegowda, Debie Hoivik, Sanjay Danthi, Gyongyi Molnar, Vilmos Csizmadia, and Michael Rabinowitz


Received January 25, 2022; accepted July 5, 2022

ABSTRACT
Pharmacological inhibition of prolyl-4-hydroxylase domain (PHD) enzymes stabilizes hypoxia-inducible factors (HIFs), transcription factors that activate target genes that, among others, increase erythropoietin (EPO) synthesis, resulting in the production of new red blood cells (RBCs). Herein, we summarize the preclinical characteristics of the small molecule HIF prolyl-4-hydroxylase inhibitor vadadustat (AKB-6548), which is in development for the treatment of anemia in patients with chronic kidney disease (CKD). Vadadustat inhibits the enzyme activity of all three human PHD isoforms, PHD1, PHD2, and PHD3, with similar low nanomolar inhibitory constant values. PHD enzyme inhibition by vadadustat is competitive with endogenous cofactor 2-oxoglutarate and is insensitive to free iron concentration. In the human hematopoietic cell line (Hep 3B) and human umbilical vein endothelial cells, PHD inhibition by vadadustat leads to the time- and concentration-dependent stabilization of HIF-1α and HIF-2α. In Hep 3B cells, this in turn results in the synthesis and secretion of EPO; vascular endothelial growth factor is not measured at detectable levels. A single oral dose of vadadustat in rats potently increases circulating levels of EPO, and daily oral dosing for 14 days increases RBC indices in healthy rats and in the 5/6 nephrectomy model of CKD. In mice and dogs, once-daily repeat oral dosing increases hemoglobin and hematocrit. Vadadustat has a relatively short half-life in all nonclinical species evaluated and does not accumulate when administered as a single bolus dose (oral or intravenous) or upon repeat oral dosing. The pharmacological profile of vadadustat supports continued development for treatment of renal anemia.

SIGNIFICANCE STATEMENT
Vadadustat (AKB-6548) is an orally bioavailable small molecule prolyl-4-hydroxylase inhibitor in development for anemia of chronic kidney disease. It is an equipotent inhibitor of the three human prolyl-4-hydroxylase domain isoforms, which activates erythropoiesis through stabilization of hypoxia-inducible factor (HIF)-1α and HIF-2α, increasing production of erythropoietin, without detectable stimulation of vascular endothelial growth factor.

Introduction
Chronic kidney disease (CKD) is a major source of morbidity and mortality worldwide and costs the healthcare industry billions of dollars annually. In addition to the risk of heart disease, stroke, and early death, patients with CKD face higher risks of developing anemia, a result of failing kidney function (US Department of Health and Human Services, 2021). Kidneys are highly metabolically active organs requiring energy to remove waste from the blood, reabsorb nutrients, regulate the balance of electrolytes and fluid, maintain acid-base balance, and excrete waste products. Additionally, kidneys produce EPO, a hormone that stimulates the production of red blood cells (RBCs). The kidney is responsible for producing as much as 90% of the body’s EPO; therefore, a decrease in kidney function results in decreased production of EPO, leading to anemia.
base homeostasis, and regulate blood pressure (Bhargava and Schnellmann, 2017). The kidneys are keenly sensitive to changes in local oxygen supply and respond to reduced oxygen (hypoxia) by interstitial fibroblasts in the cortico-medullary region producing the glycoprotein hormone erythropoietin (EPO) (Lacombe et al., 1988; Pan et al., 2011; Souma et al., 2013; Sugahara et al., 2020). EPO activates signaling through its receptor on erythroid progenitor cells in the bone marrow to stimulate proliferation and differentiation into red blood cells (RBCs), increasing the oxygen-carrying capacity of the blood (Youssoufian et al., 1993; Brxmeyer, 2013).

As the kidneys are a major source of EPO, a decline in kidney function leads to decreased EPO production that may result in anemia. The first line of treatment of anemia associated with CKD is intravenous or oral iron, followed by recombinant human EPO or similar erythropoiesis-stimulating agents (ESAs), which are the standard of care. These agents benefit patients by improving the debilitating symptoms (e.g., fatigue, shortness of breath, weakness, dizziness, depression) and reducing the dependence on blood transfusions, which are associated with secondary complications such as iron overload, infections, and sensitization impeding transplantation (Winearls et al., 1986; Eschbach, 1989). However, patients receiving ESAs also face potential adverse effects such as worsening hypertension and seizures (Winearls et al., 1986; Eschbach, 1989; Babitt and Lin, 2012). In addition, ESAs do not reduce adverse outcomes associated with anemia, such as mortality, nonfatal cardiovascular events, hospitalizations, and progression of kidney disease (KDOQI, 2006; Babitt and Lin, 2012). Thus, there remains a clinical need for effective and safer alternatives to treat anemia associated with CKD.

A recent trend in anemia management is to pharmacologically mimic mild states of physiologic hypoxia to stabilize hypoxia-inducible factors (HIFs) by preventing their degradation under normoxia (Rabinowitz, 2013). Stabilization of HIF drives gene expression and production of factors necessary for cellular adaptation to hypoxia and includes EPO, which increases erythropoiesis (Semenza and Wang, 1992). HIFs are dimeric transcription factors with three known α subunits (HIF-1α, HIF-2α, and HIF-3α) and two β subunits (HIF-1β and HIF-2β) (Wang et al., 1995; Lisy and Peet, 2008; Graham and Presnell, 2017). The α subunits are constitutively synthesized and rapidly degraded under normal (physiologic) tissue oxygenation. Oxygen-dependent HIF degradation is initiated by three iron-containing 2-oxoglutarate (2-OG)-dependent oxygenases known as the prolyl-4-hydroxylase domain (PHD) enzymes PHD1, PHD2, and PHD3 (also known as EGLN2, EGLN1, and EGLN3, respectively) (Epstein et al., 2001; Haase, 2017; Schodel and Ratcliffe, 2019). PHDs use molecular oxygen to hydroxylate specific proline residues on HIF-α subunits, which then serve as recognition tags for binding of the von Hippel Lindau (VHL) E3 ubiquitin ligase complex that subsequently leads to ubiquitylation and proteasomal degradation of the α subunits (Ivan et al., 2001; Jaakkola et al., 2001). Enzyme activity of PHDs is inhibited via substrate (molecular oxygen) depletion during hypoxia, allowing the HIF-α subunits to escape proline hydroxylation-mediated degradation, dimerize with the HIF-β subunit, translocate to the nucleus, and initiate transcription of a large set of genes, such as EPO, that are controlled with a hypoxia response element in their promoter (Wenger et al., 2005). PHD enzyme activity also can be inhibited by nonlabile structural analogs of 2-OG that bind to the active site and block both 2-OG and catalytic enzyme activity (Rabinowitz, 2013). Several small molecule PHD inhibitors (PHIs) are undergoing clinical evaluation for safety and efficacy in anemia associated with CKD to serve as orally bioavailable alternative treatment options to ESAs (Sanghani and Haase, 2019), thereby initiating erythropoiesis in a potentially more orchestrated manner than with ESAs alone. Vadadustat (Akebia Therapeutics, Inc., Cambridge, MA) is one such PHI under development for the treatment of anemia associated with CKD (Markham, 2020). Herein, we summarize the preclinical characterization of vadadustat determined by in vitro assays, which describe mechanism of action, and in vivo models, which describe exposure and pharmacodynamic effect.

Materials and Methods

Vadadustat

Vadadustat (molecular weight, 306.7 g/mol) was synthesized and micronized by Evonik Corporation (Lafayette, IN) (Sanghani and Haase, 2019). Chemical identity and purity were confirmed by infrared spectroscopy, X-ray powder diffraction, NMR, and high-performance liquid chromatography. For in vitro studies, vadadustat was dissolved in DMSO as a 10 mM stock solution and stored at −20°C, protected from light. For in vivo studies, vadadustat was prepared as described in the respective sections below.

Vadadustat-O-glucuronide (molecular weight, 483 g/mol) was synthesized by Syncom (Groningen, The Netherlands). Identity was confirmed by mass spectrometry, and purity > 98.5% was measured by high performance liquid chromatography-ultraviolet (254 nm). Vadadustat-O-glucuronide was dissolved in DMSO as a 10 mM stock solution and stored at −20°C, protected from light.

X-ray Crystallography

Purified PHD2181-416 was generated as described by Hewitson et al. (2007) and used at 12 mg/mL (0.45 mM) in a buffer consisting of 10 mM Tris pH 7, 100 mM NaCl, and 0.5 mM tris(2-carboxyethyl) phosphine; 0.1 mL aliquots were flash-frozen for crystallization trials. For analysis, cocrystals with vadadustat were produced by sitting drop vapor diffusion against 100 mM Na acetate, pH 5.5, 21% PEG1500, 15% 2-methyl-2,4-pentanediol, and 0.3 M MgSO4. The data set was collected at the Argonne Advanced Photon Source (Argonne National Laboratory, Lemont, IL) using beamline 24ID. The structure of PHD2181-416 and vadadustat was solved using the Phenix suite of programs. Specifically, the Phenix.ligand_pipeline module was used to solve the structure by molecular replacement using the program Phaser with a protein-only version of Protein Data Bank ID 3OUH as a search model and subjecting the resulting solution to autobuilding and restrained refinement. The electron density map from the pipeline solution was visually examined for evidence of ligand binding. The model of PHD2-ligand complexes was then refined using alternating rounds of manual rebuilding in Coot and restrained refinement with Phenix. Ligand model restraints were generated using the program GAMESS and Akebia-provided SMILES strings as starting points.

Enzymatic Assay for PHD1, PHD2, and PHD3

The time-resolved fluorescence resonance energy transfer (TR-FRET) assay was used to measure the enzymatic activity of vadadustat against recombinant human PHD1, PHD2, and PHD3.

All chemicals and materials unless otherwise noted were of standard laboratory grade and were purchased from Sigma-Aldrich (St. Louis, MO).
Reagents. TR-FRET reagents were as follows: monoclonal antibody anti-6His-Tb-cryptate Gold and streptavidin (SA-D2) were purchased from CsBio International (Bedford, MA). N-terminus biotinylated HIF-1α C35 synthetic peptide representing amino acids 547 to 581 and including the proline 564 PHD2 hydroxylation site was purchased from Cambridge Peptide Research (Salt Lake City, UT).

Recombinant proteins included the following: For the VBC complex, His-tagged recombinant VHL protein, ELoB, ELoC complex (His-VBC) was supplied by Axxam (Milan, Italy). Recombinant human VHL [National Center for Biotechnology Information (NCBI) accession number NP_095421.1] contained a His-tag at the C terminus of amino acids 55–213 and is referred to as VHL-His. VHL-His was coexpressed in Escherichia coli with full-length human ELoB (NCBI accession number Q15370.1) and full-length human ELoC (NCBI accession number Q15369.1) and purified by affinity chromatography on a nickel-nitrilotriacetic acid column as the His-VBC complex. Purity (~80%) was assessed by SDS-PAGE. Recombinant human PHD1 protein was purchased from Active Motif (Carlsbad, CA). PHD1 was expressed in a baculovirus expression system as the full-length protein (NCBI accession number NP_542770.2) with an N-terminal FLAG tag (molecular mass, 44.9 kDa). Purity (>90%) was assessed by SDS-PAGE. The full-length human PHD2 enzyme was produced with a baculovirus-infected insect cell expression system manufactured by Berylhum (Bedford, MA). The PHD2 construct contained amino acids 1–426 of PHD2 (UniProt Knowledgebase (UniProtKB/Swiss-Prot accession number Q8GZT9.1) and a His-tag and a tobacco etch virus protease cleavage site at the N terminus. The construct was expressed in Sf9 insect cells, purified by nickel-nitrilotriacetic acid column, and digested with tobacco etch virus protease to remove the His tag. The purity of final cleaved protein was assessed by SDS-PAGE and was found to be >94% pure. Recombinant human PHD3 protein (molecular mass, 31.1 kDa) was purchased from Active Motif (Carlsbad, CA). It was expressed in E. coli as the full-length protein (NCBI accession number NP_071356.1) with an N-terminal 6-His tag. Purity was assessed by SDS-PAGE and was found to be >75%.

TR-FRET Assay Procedure. Vadadustat was preincubated with PHD enzyme in a 10 μL reaction volume in white 384-well OptiPlate microplates (PerkinElmer, Waltham, MA). This entailed serial dilution of 5 μL vadadustat with dilution buffer (50 mM HEPES pH 7.5, 50 mM NaCl, 0.01% Tween 20, and 0.01% purified bovine serum albumin) and mixed with 5 μL PHD enzyme mix prepared as a 4X concentrate in the dilution buffer containing PHD enzyme (50 nM PHD1, 20 nM PHD2, and 140 nM PHD3), 40 μL reaction volume in white 384-well OptiPlate microplates to achieve 40 μM vadadustat in the assay buffer. The IC₅₀ values were determined using a four-parameter curve fit using GraphPad Prism 7.0 as described above.

Estimation of Inhibition Constants for Vadadustat. The IC₅₀ values were converted to inhibition constants (Ki) using the Cheng-Prusoff equation as described previously for another similar PHD inhibitor (Barrett et al., 2011):

\[ Ki = \frac{IC_{50}}{1 + [S]/K_m} \]  

where Ki is the inhibition constant; IC₅₀ is the concentration of inhibitor that reduces the enzyme activity to half; [S] is the 2-OG concentration in the TR-FRET assay reactions, which is 1000 nM (10⁻⁹ M); \( K_m \) is the 2-OG concentration at which the PHD enzyme activity is at half maximal. The 2-OG \( K_m \) for PHD1, PHD2, and PHD3 were predetermined as 12.68 nM, 22.64 nM, and 79.5 nM, respectively. pKi is the negative logarithmic value of Ki (–logKi).

Competition with 2-Oxoglutarate. To assess whether vadadustat was competitive with 2-OG, TR-FRET assays with PHD2 were performed as described above, except three different concentrations of PHD2 (4 nM, 12.64 nM, 40 nM) were used to determine the 4X concentrations to make the final assay reaction contain 1 nM–10 μM 2-OG. The concentrations [log(M)] of vadadustat were plotted against the concentrations of 2-OG [log(M)] as described using GraphPad Prism 7.0.

Effect of Iron. Sensitivity of Inhibition to Iron. To evaluate the effect of iron (II) on the ability of vadadustat to inhibit PHD2, TR-FRET assays were performed as described above, except three different concentrations of the prototypical iron chelator deferoxamine (DFO) (positive control) and the 2-oxoglutarate analog dimethyloxalylglycine (DMOG) (negative control) were added to the assay buffer. The IC₅₀ values were determined using a four-parameter curve fit using GraphPad Prism 7.0 as described above.

Protein-Free Iron Binding Assay. The reactions were carried out in a 100 μL reaction volume in black 96-well OptiPlate microplates. For this, 50 μL compound was serially diluted with dilution buffer (20 mM HEPES pH 7.5, 150 mM NaCl) and mixed with 50 μL calein mix prepared as a 2X concentrate in the dilution buffer containing 0.4 μM calein, 0.4 μM FAS, and 2 mM sodium ascorbate in 20 mM HEPES pH 7.5 and 150 mM NaCl. The plates were incubated for 2.5 hours at RT in the dark without rotation. The final assay reaction contained 0.2 μM calein, 0.2 μM FAS, and 1 mM sodium ascorbate in 20 mM HEPES pH 7.5 and 150 mM NaCl. Calein fluorescence was then read on an EnVision plate reader at an excitation wavelength of 485 nm and an emission wavelength of 520 nm.

The intensity of the calein emission fluorescence at a wavelength of 520 nm was plotted against the concentration of the compound. The dequenched fluorescence detected after incubation with the test article was compared with the fluorescence measured in the presence of the prototypical iron chelator deferoxamine (DFO) (positive control) and the 2-oxoglutarate analog dimethylglycine (DMOG) (negative control).

MesoScale Discovery Technology. MesoScale Discovery Technology (MSD) technology was used to measure the stabilization of HIF-1α and HIF-2α. All components for this evaluation were purchased from MesoScale Diagnostics (Rockville, MD) unless otherwise specified. The human hepatocarcinoma cell line (Hep 3B) and human umbilical vein endothelial cells (HUVEC) were purchased from ATCC (Manassas, VA). Hep 3B or HUVEC cell lines were plated in each well of a 96-well cell culture plate and incubated at 37°C in an incubator maintaining a
humidified, 95% air/5% CO₂ atmosphere. When a confluent monolayer was achieved, the cell culture media was replaced with media containing varying concentrations of vadadustat, and the plate was returned to the incubator. After 6 or 24 hours of incubation, the media was aspirated, and cells were rinsed with PBS and lysed with a nonenzymatic Tris lysis solution from MSD. The lysate was clarified by centrifugation, and the protein content was measured using the BCA protein assay (ThermoFisher Scientific, Waltham, MA). The cell lysate from the wells of the cell culture plate was applied to corresponding wells of a 96-well MSD plate precoated either with a HIF-1α or HIF-2α capture antibody (R&D Systems, Minneapolis, MN). After incubation at room temperature for 1 hour, the wells were washed three times with a MSD Tris Wash Buffer and then incubated for another hour with a detection antibody, which, in the case of HIF-1α, was pre-conjugated with a SulfoTag. For HIF-2α, a biotinylated detection antibody (R&D Systems) was added. For HIF-2α, the detection antibody step was followed by an additional wash and further incubation with a SulfoTag-conjugated streptavidin. The plates were washed, an enhanced chemiluminescence read buffer was added to the wells, and chemiluminescence was measured on a MesoQuickPlex SQ120 plate reader. The readings were converted to pg/mL of HIF-1α or HIF-2α by interpolating to a standard curve for the respective analyte. Finally, the analyte concentrations were converted to pg/mg of lysate by normalizing to the amount of total protein in each lysate and plotted against the vadadustat concentration to generate a concentration response curve.

**Quantification of EPO and Vascular Endothelial Growth Factor A Release**

The effect of vadadustat effect on EPO release was quantified from culture supernatants of Hep 3B cells using the Human Erythropoietin Quantikine IVD enzyme-linked immunosorbent assay ELISA kit (R&D Systems). Cells were grown in Eagle’s Minimal Essential Media, supplemented with 2 mM GlutaMax, 1 mM Na-pyruvate, and 10% FBS (growth medium). For this assay, Hep 3B cells were seeded at a density of 40,000 cells per well in growth medium in a 96-well plate format. After incubation at 37°C, 5% CO₂ for 6 hours, the medium was replaced by growth medium without FBS and cultured overnight. The following morning, different concentrations of vadadustat were added to the wells in a 100 µL per well final volume and the cells were incubated for an additional 24 hours. At the end of the treatment, supernatants were collected from the wells, and EPO release was immediately measured with the human EPO sandwich ELISA kit following the manufacturer’s protocol. Briefly, equal amount of culture supernatants from each well or diluted standards (recombiant human EPO) were added to the appropriate antibody precoated wells and incubated at RT. After 1 hour, the contents of the wells were replaced by EPO conjugate reagent and the incubation was continued at RT for 1 hour. After washing the plate four times with assay wash buffer, the substrate solution was employed for 15 minutes. The color was developed when stop solution was added to the wells. Yellow color intensity was read at 450 nm with a microplate reader (SpectraMax M3, Molecular Devices, San Jose, CA). EPO levels in response to vadadustat treatment at different concentrations were calculated according to the assay standard curve. All data points were in the linear detection range of the kit (2.5 mIU/mL–200 mIU/mL).

Secreton human vascular endothelial growth factor A (VEGFA) was measured from the culture supernatant of Hep 3B cells using the human VEGF Quantikine ELISA kit (R&D Systems). Hep 3B cells were plated in 96-well plates at a 10,000-cells-per-well density in growth medium and then incubated overnight at 37°C at 5% CO₂. The next day, different concentration of vadadustat were added to the growth medium, and the cells were further cultured for 24 hours. Culture supernatants were then collected and assayed by VEGF sandwich ELISA according to the manufacturer’s protocol. Briefly, standards and samples were pipetted into the antibody precoated wells for a 2-hour incubation time at RT. After washing away any unbound substances, an enzyme-linked polyclonal antibody specific for human VEGFA was added to the wells for another 2 hours. Following the wash of any unbound antibody-enzyme reagent, the enhanced luminol/peroxide substrate solution was added to the wells and incubated for 20 minutes at RT, protected from light. Finally, light activity was measured by EnVision plate reader, and VEGF concentration was calculated using the standard curve.

**In Vivo Studies**

All in vivo studies were carried out at Charles River Laboratories, accredited by the Association for Assessment and Accreditation of Laboratory Animal Care International, in accordance with the Guide for the Care and Use of Laboratory Animals from the USA National Research Council and the guidelines from the Canadian Council on Animal Care for those studies conducted in Canada.

**Pharmacokinetic Parameters of Vadadustat**

To characterize the pharmacokinetic (PK) parameters of vadadustat, single or repeat doses of vadadustat were administered to Sprague-Dawley Crl:CD (SD) rats, beagle dogs, and CByB6F1 hybrid mice as described below. Blood samples (approximately 0.5 mL each) were collected via percutaneous cardencocentesis or from the vena cava (from animals anesthetized with isoflurane) into tubes containing K₂EDTA and 1% (v/v of blood collected) of 1 M citric acid solution, mixed by inversion, and stored on wet ice until centrifuged at 1800 × g within 30 minutes of collection to separate the plasma. Plasma was placed into chilled polypropylene tubes containing approximately 2% (v/v of plasma in tube) glacial acetic acid and stored frozen (approximately 70°C) until analyzed for the concentration of vadadustat using a validated ultra-high performance liquid chromatography-tandem mass spectrometry bioanalytical procedure.

**Single-Dose PK of Vadadustat.** To evaluate the PK properties of a single dose of vadadustat, male and female SD rats (n = 6 per sex per dosing group) and beagle dogs (n = 3 per sex per dosing group) were administered a single dose of intravenous vadadustat at 5.57 mg/kg (rats) or 5 mg/kg (dogs) prepared in pH-adjusted sterile water or by oral gavage at 20 mg/kg (rat) or 30 mg/kg (dog) as a suspension in 0.25% (w/v) hydroxypropyl methyl cellulose (HPMC; 4000 cP)/0.1% (w/v) Tween 80 in ultrapure water. Nonserial (composite 3 rats/timepoint) and serial (dog) blood samples were collected from individual animals at the following time points: 0 (predose), 0.05 (intravenous only), 0.25, 0.5, 1, 2, 3 (oral only), 4, 6, 8, 12, 24, and 48 hours postdose.

**Repeat-Dose PK of Vadadustat.** SD rats (n = 3 per sex per dosing group), beagle dogs (n = 5 per sex per dosing group), and CByB6F1 hybrid mice (n = 18 per sex per dosing group; n = 3 per sex per timepoint) were administered 100 mg/kg (male) or 120 mg/kg (rats and dogs) of vadadustat once daily by oral gavage formulated in 0.25% (w/v) HPMC; 4000 cP/0.1% (w/v) Tween 80 in ultrapure water. Nonserial (mouse) and serial (rat and dog) blood draws were collected from individual animals at 0 (predose), 1, 2, 4, 8, 12 (dog only), and 24 hours postdose.

**In Vivo Hematologic Effects of Vadadustat**

A detailed analysis of the pharmacodynamic effects of vadadustat was conducted in male SD rats after single oral gavage doses of 50 or 150 mg/kg vadadustat formulated in 0.25% (w/v) HPMC; 4000 cP/0.1% (w/v) Tween 80 in ultrapure water (n = 15 rats per dose level) (n = 3 per timepoint). At 0, 1, 3, 6, 24, and 48 hours after dosing, 2 mL of whole blood was collected from each rat by jugular venepuncture into serum separator tubes, allowed to clot at room temperature, and subsequently centrifuged for 10 minutes in a refrigerated centrifuge (set to maintain 4°C) at 1400g. The resultant serum was separated, transferred to a polypropylene tube, frozen immediately over dry ice, and then transferred to a freezer set to maintain ~80°C until analysis.
Serum samples underwent EPO analysis using the LEGEND MAX Rat Erythropoietin ELISA Kit (BioLegend, San Diego, CA). Rat serum samples were analyzed in duplicate using qualified analytical procedures.

Hematologic parameters were measured in male SD rats after daily oral gavage dosing of vehicle or vadadustat at 30 or 90 mg/kg for 14 days, formulated as described above (n = 10–12 rats per group). On day 14, 0.5 mL of whole blood was collected into EDTA-containing tubes and analyzed on an Advia 120 Automated Hematology Analyzer (Siemens, Malvern, PA).

To assess the exposure response relationship between hematocrit (HCT), hemoglobin (Hgb), and area under the curve (AUC), data were combined from multiple studies conducted in male and female SD rats (1–48 months in duration), beagle dogs (1–9 months in duration), and CByB6F1 hybrid mice (2–6 months in duration). Animal numbers were as follows: for rats, 181 males and 184 females; for dogs, 89 males and 89 females; and for mice, 174 males and 170 females. In brief, rats, dogs, and mice were administered a range of doses (5–300 mg/kg/d) of vadadustat once daily by oral gavage formulated in 0.25% (w/v) HPMC; 4000 cP/0.1% (w/v) Tween 80 in ultrapure water.

5/6 Nephrectomy Model of CKD. Male SD rats (250 ± 20 g) underwent 5/6 nephrectomy by ligation and removal of the upper and lower third of the left kidney, followed by removal of the contralateral right kidney 1 week later. Six weeks after surgery completion, treatment with vehicle (n = 20) or vadadustat (n = 25 per dose group) was started by daily oral dosing (30 mg/kg or 90 mg/kg) for 14 days. Vadadustat was prepared in 0.25% (w/v) HPMC/0.1% (w/v) Tween 80 in ultrapure water. Blood samples were collected from the retro-orbital sinus in K2EDTA on day 0 and day 14 for hematocrit; RBC indices were measured on an Advia 120 Automated Hematology Analyzer. Serum was collected into serum separator tubes and measured for creatinine and urea nitrogen on an Advia 1800 Chemistry Analyzer (Siemens, Malvern, PA). Kidneys were excised and fixed in 10% neutral buffered formalin, followed by paraffin embedding, sectioning, and staining with hematoxylin-eosin.

Statistical Analyses

The data were analyzed and/or graphed using GraphPad Prism. Differences in EPO and VEGF secretion were evaluated by Tukey multiple comparison test. Differences in RBC indices were evaluated by Kruskall-Wallis and Dunn test or ANOVA and Dunnett’s multiple comparison test.

Results

In Vitro Pharmacological Characterization of Vadadustat

Vadadustat (2-[[5-(3-chlorophenyl)-3-hydroxypyridine-2-carbonyl]amino]acetic acid) (Fig. 1A) was designed as a nonlabile active site 2-OG mimetic inhibitor of the HIF-PHD enzymes. Electron density measurements of the X-ray structure of a cocrystal of vadadustat and an iron-containing catalytic site construct of the PHD2 isoform (Fig. 1B) show the presence of two Cl-phenyl ring rotamers in roughly equal populations. As expected, vadadustat bound to the catalytic site of PHD2 at a resolution of 1.8Å and made bidentate chelation interactions with the active site Fe atom as well as a salt bridge interaction with Arg383 deep in the binding pocket, H-bond interaction of the vadadustat phenolic OH with Tyr303, and nonspecific lipophilic interactions of the chlorophenyl ring with residues near the HIF binding site. Resolution achieved was 1.8Å.

Vadadustat inhibited full-length recombinant human PHD1, PHD2, and PHD3 enzymes. Based on the TR-FRET assay, which measures the interaction between the VBC complex and hydroxylated HIF-1α (produced by recombinant PHDs) in the presence of increasing concentrations of vadadustat, the pKi values (geometric mean and 95% CI) for PHD1, PHD2, and PHD3 were 9.72 (9.61, 9.82), 9.58 (9.42, 9.74), and 9.25 (9.23, 9.27), respectively (Fig. 2, A–C; Table 1). Enzymatic activity of vadadustat-O-glucuronide, a major metabolite of vadadustat, was also measured by the TR-FRET assay with PHD2 enzyme. The Ki (nM) and pKi values (geometric mean and 95% CI) were 51.1 (38.5, 68.2) and 7.29 (7.17, 7.41), respectively (Fig. 2D), suggesting that vadadustat-O-glucuronide metabolite was approximately 200-fold less potent a PHD inhibitor than vadadustat itself. Additionally, vadadustat is a competitive inhibitor of PHD2. Concentration-effect curves constructed across a range of 2-OG concentration versus a range of vadadustat concentrations using the TR-FRET assay with PHD2 enzyme indicated competitive inhibition with 2-OG (Fig. 2E). Inhibition of PHD2 enzyme by vadadustat in the presence of increasing iron concentrations was also measured to evaluate the effect of added iron on the IC50 of vadadustat (Fig. 2F). The IC50 value of vadadustat was found to be relatively insensitive to increasing iron concentrations, suggesting that vadadustat is not a
potent chelator of free iron under the assay conditions. The IC50 values (nM) of vadadustat in the presence of 100 nM Fe2+
were 211.10 ± 40.81, 8.46 ± 0.77, and 5.12 ± 0.82, respectively. Additionally, to assess the affinity of vadadustat for free iron, a protein-free assay based on calcein fluorescence was carried out (Barrett et al., 2011). As expected, DFO showed strong iron binding, whereas DMOG demonstrated minimal iron binding. Vadadustat exhibited weak iron chelation compared with DFO (Fig. 2G). Thus, based on in vitro pharmacological characterization, vadadustat was found to be a potent inhibitor of isolated and purified human PHD1, PHD2, and PHD3 enzymes that is competitive with 2-OG and not strongly affected by local iron levels.

Vadadustat Stabilizes HIF-1α and HIF-2α in Multiple Cell Lines

Next, the ability of vadadustat to stabilize HIF-1α and HIF-2α was evaluated. Consistent with its ability to inhibit the three PHD enzyme isoforms, vadadustat stabilized HIF-1α and HIF-2α in Hep 3B cells and the HUVEC line in a dose-dependent manner (Fig. 3). Stabilization of both HIFs was sustained for the duration of vadadustat exposure (6 or 24 hours), measured with MSD technology. In Hep 3B cells, vadadustat

<table>
<thead>
<tr>
<th>PHD Enzymes</th>
<th>Ki Value (nM)</th>
<th>pKi Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHD1</td>
<td>0.19 (0.15, 0.25)</td>
<td>9.72 (9.61, 9.82)</td>
</tr>
<tr>
<td>PHD2</td>
<td>0.26 (0.18, 0.38)</td>
<td>9.58 (9.42, 9.74)</td>
</tr>
<tr>
<td>PHD3</td>
<td>0.56 (0.53, 0.59)</td>
<td>9.25 (9.23, 9.27)</td>
</tr>
</tbody>
</table>

Table 1: Ki and pKi values of vadadustat against human PHD enzymes

Fig. 2. Biochemical characterization of vadadustat. Concentration-response curves of PHD activity against test articles [log (M), x-axis] are shown in (A–D) and (F). The test article for (A–C) and (F) is vadadustat; for (D), it is vadadustat-O-glucuronide. The PHD enzymes examined in (A) and (C) are PHD1 and PHD3, respectively. PHD2 is used in (B), (D), and (F). The y-axis represents the residual mean and standard deviation data from the three replicates for each experiment. These values are normalized to basal activity without test article (100%). Expt #1, Expt #2, and Expt #3 represent the three independent experiments performed for each PHD enzyme. (A–C) Vadadustat inhibits recombinant human PHD1, PHD2, and PHD3 at equivalent nanomolar concentrations. (D) Vadadustat-O-glucuronide inhibits recombinant human PHD2 at micromolar concentration. (E) Vadadustat is a competitive inhibitor of 2-OG. The TR-FRET assay is performed by using PHD2 enzyme. The concentrations [log (M)] of vadadustat are shown on the right side of the graph, and concentrations of 2-OG [log (M)] tested are shown on the x-axis. The calculated ratios of the emission wavelength (665 nm/615 nm) are represented by the y-axis. (F) Vadadustat inhibition of recombinant human PHD2 is not sensitive to iron concentration. PHD2 activity against vadadustat in the presence of three different concentrations of FAS. (G) Iron-binding property of vadadustat. The iron binding of vadadustat, DFO, and DMOG is measured by fluorescence intensity. DFO and DMOG served as positive and negative controls, respectively, for their iron chelation activities. Data from one of the three independent experiments are shown. Expt, experiment.
treatment increased HIF-1α with a half-maximal EC₅₀ of 44 μM and 67 μM over 6 and 24 hours, respectively, and increased HIF-2α with an EC₅₀ of 51 μM and 54 μM over 6 and 24 hours, respectively. In the HUVEC line, vadadustat treatment increased HIF-1α with an EC₅₀ of 25 μM and 71 μM over 6 and 24 hours, respectively, and increased HIF-2α with an EC₅₀ of 21 μM and 38 μM over 6 and 24 hours, respectively.

Vadadustat Stimulates EPO Secretion but Not VEGF

Stabilization of HIF-1α and HIF-2α by PHD inhibition results in the mRNA transcription of HIF target genes, such as EPO and VEGF. The effect of vadadustat on EPO and VEGF release by Hep 3B cells was assayed in vitro at drug concentrations ranging from 0.1 to 100 μM (Fig. 4). At concentrations above 3 μM, vadadustat significantly increased EPO secretion by Hep 3B cells, reaching greater levels of EPO release at 30 μM (Fig. 4A). The calculated EC₅₀ was 9.97 μM, and at this concentration, the maximal EPO release was 12.04 mIU/mL (Fig. 4A).

The effect of vadadustat on VEGF secretion was evaluated similarly. Vadadustat did not increase VEGF secretion by Hep 3B cells at the investigated doses of 3 μM, 10 μM, and 30 μM compared with the 1% hypoxia control (Fig. 4B).

In Vivo Characterization of Vadadustat

Based on the in vitro data demonstrating PHD inhibition, HIF stabilization, and EPO secretion with vadadustat treatment, the in vivo hematologic effects of vadadustat and PK were evaluated.

Single-Dose Vadadustat PK. PK parameters in SD rats (Fig. 5A; Table 2) and beagle dogs (Fig. 5B; Table 3) after the administration of an intravenous or oral dose of vadadustat were derived from concentration-time curves. In SD rats, plasma clearance (CL) after intravenous administration was low, with values of 145 mL/h per kg and 226 mL/h per kg for males and females, respectively. The apparent volume of distribution at steady state (Vss) after intravenous administration was low, with values of 182 mL/kg and 258 mL/kg for males and females, respectively. The time to maximum concentration (Tₘₐₓ) after a single oral dose ranged from 0.5 to 2 hours. The half-life (T½) was relatively short, ranging from 1 to 2 hours. Vadadustat exhibited high oral bioavailability, with a calculated sex-combined estimated oral bioavailability (%F) > 90% normalized for a 20 mg/kg oral dose. There were no notable sex differences in systemic exposure. In beagle dogs, a linear elimination phase was not observed upon intravenous administration in both sexes or upon oral administration in males. A lack of an observed linear elimination phase precludes the acceptable calculation of PK parameters such as Cₘₐₓ and Tₘₐₓ.
as CL, Vss, T1/2, and AUC0–inf. Following a single oral dose of 30 mg/kg, mean Cmax values were 50,900 ng/mL and 62,800 ng/mL, and AUC0–t values, defined as area under the curve to last measurable concentration, were 156,000 ng/C15h/mL and 109,000 ng/C15h/mL for males and females, respectively. There was no notable sex difference in plasma Cmax or AUC0–t values in this study. High oral bioavailability in the dogs was noted based on comparisons of dose-normalized AUC0–t following oral administration to AUC0–t following intravenous administration.

Repeat-Dose Vadadustat PK. PK parameters of vadadustat were measured in mice, rats, and dogs after a single oral dose or after daily dosing for 28 or 56 days as shown in Table 4. Exposure to vadadustat, in terms of AUC0–t, was similar on study day 1 and at end of study (day 28 and day 56). The accumulation ratio for all three species was approximately 1 or less than a value of 1, suggesting no accumulation. The T1/2 for vadadustat in mice and rats was approximately 2 hours and in dogs was approximately 3 hours. The dose-normalized group mean AUClast was greatest for rats, followed by dogs and mice.

Effect on Serum EPO in Normal Rats after a Single Dose. A dose-dependent increase in serum EPO concentration was measured in normal SD rats after a single intravenous bolus dose of 5.57 mg/kg and a single oral dose of 20 mg/kg. Data represent the mean plus or minus standard deviation of n = 3 per timepoint. (B) Mean plasma concentration for vadadustat in male and female beagle dogs after a single intravenous bolus dose of 5 mg/kg and a single oral dose of 30 mg/kg. Data represent the mean plus or minus standard deviation of 3 animals per timepoint. (C) EPO release in male Sprague-Dawley rats after a single oral administration of vadadustat at 50 mg/kg or 150 mg/kg. Data represent the mean plus or minus standard deviation of n = 3. Conc., concentration; IV, intravenous.

Table 4. Exposure to vadadustat, in terms of AUC0–t, was similar on study day 1 and at end of study (day 28 and day 56). The accumulation ratio for all three species was approximately 1 or less than a value of 1, suggesting no accumulation. The T1/2 for vadadustat in mice and rats was approximately 2 hours and in dogs was approximately 3 hours. The dose-normalized group mean AUClast was greatest for rats, followed by dogs and mice.

Effect on Serum EPO in Normal Rats after a Single Dose. A dose-dependent increase in serum EPO concentration was measured in normal SD rats after a single dose (Fig. 5C). At dose levels of 50 and 150 mg/kg, serum concentrations of EPO were noted to increase 3 hours postdose and reached a peak concentration 6 hours after administration. EPO levels remained elevated compared with predose levels 24 hours
Hemoglobin across Multiple Species. In mice, rats, and dogs, there was an exposure-response relationship between vadadustat for 14 days at 30 mg/kg or 90 mg/kg (Fig. 6A). Hgb, HCT, reticulocyte count, mean corpuscular volume, mean corpuscular Hgb, and RBC distribution width were elevated compared with predose levels (day 0) after daily oral dosing for 14 days with 90 mg/kg of vadadustat.

**Exposure-Dependent Increase in Hematocrit and Hemoglobin across Multiple Species.** In mice, rats, and dogs, there was an exposure-response relationship between vadadustat plasma AUCₜₐ₀−ₜ, and both HCT and Hgb levels (Fig. 6B). The duration of treatment of normal animals was as follows: mice up to 6 months, rats up to 2 years, and dogs up to 9 months. The maximal HCT increase from baseline for mice, rats, and dogs was 91.9%, 67.9%, and 66.5%, respectively, without any effect from animal sex. The maximum effect relative to baseline corresponded to net increases of 92.5% (mice), 60.8% (rats), and 38.7% (dogs) for females. Any apparent species differences in baseline HCT and Hgb were considered to be within the standard deviation and biologic variability and were considered comparable.

**Effect on RBC Indices in Normal Rats after 14 Days of Daily Oral Dosing.** RBC indices in normal rats increased in a dose-dependent manner after daily oral administration of vadadustat for 14 days at 30 mg/kg or 90 mg/kg (Fig. 6A). Hgb, HCT, reticulocyte count, mean corpuscular Hgb, and RBC distribution width were elevated compared with predose levels (day 0) after daily oral dosing for 14 days with 90 mg/kg of vadadustat.

**Effect on RBC Indices in the Rat 5/6 Nephrectomy Model of CKD after 14 Days of Daily Oral Dosing.** The effect of vadadustat on hematologic parameters in the 5/6 nephrectomy model of CKD was investigated. Six weeks after the completion of surgical procedures to induce CKD, the rats were dosed daily for 14 days with 30 mg/kg or 90 mg/kg of vadadustat by oral gavage. RBC indices were measured before (day 0) and after (day 14) treatment (Fig. 7). The vehicle-treated group did not show any significant changes in RBC parameters between day 0 and day 14. In contrast, vadadustat dose-dependently increased Hgb, HCT, reticulocyte counts, mean corpuscular volume, mean corpuscular Hgb, and RBC distribution width between day 0 and day 14, with the greatest increases that reached statistical significance measured at 90 mg/kg vadadustat after 14 days of oral dosing in this model of kidney impairment. Changes in HCT were also statistically significant and were higher at 30 mg/kg.

There were no statistically significant changes in body weight (mean plus or minus standard deviation) between the vehicle (439 ± 29.6 g) and vadadustat-treated groups after 14 days of daily oral dosing.

---

**TABLE 2**

Single-dose pharmacokinetics of vadadustat in the Sprague-Dawley rat

<table>
<thead>
<tr>
<th>Route</th>
<th>Dose</th>
<th>T₁/₂ (h)</th>
<th>Cmax (ng/mL)</th>
<th>Tₘₐₓ (h)</th>
<th>AUC₀−ₜ (ng·h/mL)</th>
<th>AUC₀−ₜ inf (ng·h/mL)</th>
<th>DN AUC₀−ₜ inf (ng·h/mL)</th>
<th>CL (mL/kg)</th>
<th>Vₐ (mL/kg)</th>
<th>Vₐ*(mL/kg)</th>
<th>%F (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intravenous Bolus</td>
<td>5</td>
<td>0.99</td>
<td>29,100</td>
<td>0.05</td>
<td>31,700</td>
<td>31,700</td>
<td>5690</td>
<td>176</td>
<td>212</td>
<td>91</td>
<td></td>
</tr>
<tr>
<td>Oral</td>
<td>20</td>
<td>2.1</td>
<td>28,100</td>
<td>0.50</td>
<td>104,000</td>
<td>104,000</td>
<td>5200</td>
<td>NC</td>
<td>NC</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

AUC₀−ₜ inf, area under the curve to infinity; DN AUC₀−ₜ inf, area under the curve to infinity normalized to dose; NC, not calculated.

**TABLE 3**

Single-dose pharmacokinetics of vadadustat in the beagle dog

<table>
<thead>
<tr>
<th>Route</th>
<th>Dose</th>
<th>T₁/₂ (h)</th>
<th>Cmax (ng/mL)</th>
<th>Tₘₐₓ (h)</th>
<th>AUC₀−ₜ (ng·h/mL)</th>
<th>AUC₀−ₜ inf (ng·h/mL)</th>
<th>DN AUC₀−ₜ inf (ng·h/mL)</th>
<th>CL (mL/kg)</th>
<th>Vₐ (mL/kg)</th>
<th>Vₐ*(mL/kg)</th>
<th>%F (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intravenous Bolus</td>
<td>5</td>
<td>0.99</td>
<td>29,100</td>
<td>0.05</td>
<td>31,700</td>
<td>31,700</td>
<td>5690</td>
<td>176</td>
<td>212</td>
<td>91</td>
<td></td>
</tr>
<tr>
<td>Oral</td>
<td>20</td>
<td>2.1</td>
<td>28,100</td>
<td>0.50</td>
<td>104,000</td>
<td>104,000</td>
<td>5200</td>
<td>NC</td>
<td>NC</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

AUC₀−ₜ inf, area under the curve to infinity; DN AUC₀−ₜ inf, area under the curve to infinity normalized to dose; NC, not calculated.

F, female; M, male; NA, not applicable; NC, not calculated.

%F was calculated using the mean dose-normalized AUC₀−ₜ oral/mean dose-normalized AUC₀−ₜ intravenous × 100%.
days of daily dosing at 30 mg/kg (435 ± 43.6 g) or 90 mg/kg (430 ± 34.9 g). Moreover, renal function did not change as measured by serum creatinine (0.82 ± 0.15 mg/dL, 0.97 ± 0.54 mg/dL, and 1.0 ± 0.22 mg/dL for vehicle, 30 mg/kg vadadustat, and 90 mg/kg vadadustat, respectively) and blood urea nitrogen (32.9 ± 7.6 mg/dL, 35.5 ± 12.1 mg/dL, and 33.7 ± 4.9 mg/dL for vehicle, 30 mg/kg vadadustat, and 90 mg/kg vadadustat, respectively). Histology did not identify differences in the severity of kidney damage between groups.

**Discussion**

Several HIF-PHIs have received marketing approval in Japan, China, and the European Union for the treatment of anemia in patients with dialysis-dependent (DD) and non-dialysis dependent (NDD) CKD (Hirota, 2021). Vadadustat, an oral HIF-PHI, became commercially available in Japan for the treatment of anemia in these same patient populations (Markham, 2020). Results of global phase 3 studies with HIF-PHIs were recently published for vadadustat, daprodustat, and roxadustat (Chertow et al., 202; Eckardt et al., 2021; Fishbane et al., 2021; Provenzano et al., 2021; Singh et al., 2021a; Singh et al., 2021b). In this report, we present the first preclinical pharmacological characterization of vadadustat, detailing in vitro molecular, biochemical, and cellular characterization and in vivo evaluation in healthy and diseased animals. We used the PHD2 enzyme to structurally and biochemically analyze vadadustat. Among the PHD enzymes, PHD2 is the main oxygen sensor (Berra et al., 2003); it is the most important PHD enzyme in setting steady-state levels of HIF-α and, hence, activity of the HIF system in oxygenated cells. PHD2 also is the most abundant PHD; it is expressed at moderate to high levels in the cytoplasm of almost all cells and tissues (Lieb et al., 2002; Metzen et al., 2003; Uhlen et al., 2015). Moreover, deletion of PHD2 is embryonic lethal because of placental and cardiac effects (Minamishima et al., 2008; Singh et al., 2013). In contrast, PHD3 is the most relevant PHD in hypoxia (Appelhoff et al., 2004). PHD1 and PHD3 have a more tissue-restricted expression (Lieb et al., 2002; Uhlen et al., 2015) and localize to the nucleus (PHD1) or to both the nucleus and cytoplasm (PHD3) (Metzen et al., 2003). PHD1 and PHD3 knockout mice are viable; deletion of PHD1 reduces exercise tolerance, whereas deletion of PHD3 affects adrenal and sympathetic nervous system development (Meneses and Wielockx, 2016). For these reasons, we used PHD2 to characterize the molecular and biochemical properties of vadadustat.

X-ray coocrystal structure determination of vadadustat bound to the catalytic domain of PHD2 revealed its target binding as an active site inhibitor, binding in the 2-OG pocket of the PHD2 enzyme in a binding pose similar to the endogenous ligand 2-OG (Rabinowitz, 2013). Concentration-responsive curves confirmed vadadustat effectively inhibited PHD enzyme in a 2-OG competitive manner. The activity of vadadustat was insensitive to added iron and did not show strong chelation of free iron, suggesting its activity is not as a general iron chelator and should not be affected by extra-enzymatic sources of iron.

Importantly, vadadustat is a pan-PHD inhibitor demonstrating equipotential inhibition of the three human PHD1, PHD2, and PHD3 enzymes. The Ki values generated by TR-FRET, which measures inhibition of HIF proline hydroxylatation with increasing concentrations of vadadustat, were in the low nanomolar range. Because vadadustat displays competitive inhibition kinetics for 2-OG, and the concentration of 2-OG in the enzyme reaction will influence the IC_{50} value, we calculated Ki values, which adjusts for the concentration of 2-OG required for inhibition of each of the PHD enzymes. Thus, based on the Ki values, our data indicate that vadadustat is a nonselective inhibitor of PHD enzymes. This contrasts with earlier reports suggesting a preference of vadadustat for PHD3 based on IC_{50} values (Yeh et al., 2017; Sanghani and Haase, 2019). Other PHIs evaluated in clinical studies, FG-4592/roxadustat, GSK1278863/daprodustat, BAY85-3934/molidustat, and JTZ-51/enarodustat, also are pan inhibitors of the human PHD enzymes (Flamme et al., 2014; Ariazi et al., 2017; del Balzo et al., 2020). Biophysical, biochemical, and cellular comparisons of FG-4592, GSK1278863, BAY85-3934, and AKB-6548 have been reported (Yeh et al., 2017); all have similar effects upregulating HIF target genes but differ in the mode of binding to the active site of PHD2, the kinetics of their effects, and the extent of inhibition of the N- and C-terminal oxygen-dependent degradation domains (Yeh et al., 2017).

Inhibition of proline-hydroxylatation activity of PHD enzymes results in stabilization of HIF-α (Semenza and Wang, 1992). Using two different cell lines, Hep 3B and HUVEC, we demonstrated that PHD inhibition by vadadustat stabilizes both HIF-1α and HIF-2α in a concentration- and time-dependent manner. Early internal studies suggested a preferential stabilization of HIF-2α by vadadustat (Shalwitz et al., 2011). However, the detailed quantitative analyses generated by MSD technology in two different cell lines in this report suggests vadadustat stabilizes both HIF-1α and HIF-2α, and stabilization of these two isoforms depends on the cell type examined (Yeh et al., 2017).

Consistent with PHD inhibition and stabilization of HIF-α is the subsequent increase in transcription of HIF-responsive genes, such as EPO, necessary for erythropoesis (Semenza and Wang, 1992). Stabilization of HIF-α in Hep 3B cells by vadadustat resulted in concentration-dependent increases in secretion of EPO. In contrast, an increase in VEGF secretion was not detected. These data are consistent with the observed improvement of hematologic parameters in CKD patients, where Hgb and HCT were corrected in phase 2 and phase 3 trials of DD- and NDD-CKD patients, yet plasma levels of VEGF were not increased (Pergola et al., 2016; Martin et al., 2017; Nangaku et al., 2021a; Nangaku et al., 2021b). Why hypoxia and some PHIs increase VEGF (i.e., molidustat/
BAY85-3934) but vadadustat and others (i.e., roxadustat/FG-4592, daprodustat/GSK1278863, and enarodustat/JTZ-951) do not (Brigandi et al., 2016; Holdstock et al., 2016; Akizawa et al., 2019; Akizawa et al., 2021) is an area for future studies.

The observation that HIF-PHIs are erythropoietic at doses that do not stimulate VEGF also warrants investigation. Possible explanations for the dissociation in expression of EPO versus VEGF include the dose and pharmacokinetics of the

**Fig. 6.** In vivo hematologic effects of vadadustat. (A) Red blood cell indices in male Sprague-Dawley rats after daily oral administration of vadadustat for 14 days at 30 mg/kg or 90 mg/kg (n = 10–12 rats/group). Hemoglobin (g/dL), hematocrit (%), RETIC (number × 10⁹/L), MCV (fL), mean corpuscular hemoglobin (pg), and RDW (%) are shown. Data represent mean plus or minus standard deviation. Statistical analysis by Kruskal-Wallis and Dunn for hematocrit, RETIC, MCV, and MCH (**P ≤ 0.001) and ANOVA and Dunnett (*P ≤ 0.05, ***P ≤ 0.01) for hemoglobin and RDW versus vehicle. (B) Multidose exposure to vadadustat in male and female mice, rats, and dogs, measured as AUC (ng*h/mL), demonstrates increases in hemoglobin and hematocrit. For mice, rats, and dogs, there were 174, 181, and 89 males, respectively, and 170, 184, and 89 females, respectively. MCH, mean corpuscular hemoglobin; MCV, mean corpuscular volume; RDW, red blood cell distribution width; RETIC, reticulocyte counts.
HIF-PHI; the regulation of EPO expression, known to be highly sensitive to hypoxia compared with other HIF targets, such as VEGF (Sandner et al., 1996; Yeh et al., 2017), including epigenetic control of the promoter region (Steinmann et al., 2011; Chang et al., 2016); and the greater HIF stabilization that may be required to activate VEGF compared with EPO (Haase 2017).

Interestingly, the Ki values for PHD activity in the TR-FRET assay were in the nanomolar range, compared with the EC_{50} values in the cell-based assays, which were in the micromolar range. This difference could be explained by the small molecule properties of vadadustat, including protein binding and plasma membrane permeability. The concentration of intracellular citric acid (Kreb’s) cycle intermediates, specifically fumarate and succinate, could also be a factor. These intermediates inhibit all three PHD enzymes (Koivunen et al., 2007). Thus, higher concentrations of vadadustat in the cell-based assays could be required to overcome endogenous intracellular competition by citric acid cycle intermediates, potentially explaining the micromolar EC_{50} values in cell-based assays versus nanomolar concentrations with TR-FRET.

Based on biochemical and cellular data highlighting vadadustat as a nonselective PHD inhibitor that leads to the production of EPO, in vivo studies were conducted. A single oral dose of vadadustat in rats elevated plasma EPO concentrations within 6 hours after dosing, decreasing to baseline 72 hours postdose. When administered once daily for 14 days to healthy rats, vadadustat dose-dependently increased Hgb, HCT, reticulocytes, and other RBC parameters. Similar effects were measured in the 5/6 nephrectomy model of CKD, indicating vadadustat’s effect on erythropoiesis was not dependent on kidney status.

Pharmacokinetic parameters of vadadustat were evaluated in multiple nonclinical species. Upon oral administration as a suspension, vadadustat showed high oral bioavailability in rats and dogs with rapid absorption. Single-dose pharmacokinetic properties were characterized by low plasma CL in rats and low to moderate plasma CL in dogs. The V_{ss} was lower than the volume of total body water in rats, whereas in dogs, the V_{ss} was similar or slightly larger than the volume of total body water. The T_{1/2} values of vadadustat following oral administration were relatively short, approximately 2 hours in mice and rats and 3 hours in dogs; pharmacokinetic properties were generally similar in male and female animals, and there was no marked difference in vadadustat AUC_{0-last} between the fed and fasted state in male beagle dogs.
Moreover, vadadustat did not show appreciable accumulation in the three species evaluated. There was a consistent positive correlation between vadadustat plasma AUC0.54 and both HCT and Hgb levels across species. A 90 mg/kg dose in normal animals was approximately 2 times and 3 times the Cmax and AUC exposures, respectively, which correlates with a 300 mg dose in humans where hematologic effects are measured (unpublished data).

Vadadustat’s mechanism of action supported progression into clinical trials for the treatment of anemia due to CKD. In phase 2 and 3 studies of DD- or NDD-CKD patients with anemia, vadadustat increased and maintained high Hgb concentration (Pergola et al., 2016; Martin et al., 2017; Haase et al., 2019; Chertow et al., 2021; Eckardt et al., 2021). In phase 3 studies, vadadustat was noninferior to darbepoetin alfa with respect to cardiovascular safety in the DD-CKD population (INNOVATE) (Eckardt et al., 2021); however, vadadustat did not meet the prespecified noninferiority criterion for cardiovascular safety in the NDD-CKD population (PROTECT) (Chertow et al., 2021).


Address correspondence to: Dr. Anna Zuk, Department of Research and Early Development, Akebia Therapeutics, Inc., 245 First Street, Cambridge, MA 02142. E-mail: AZuk@akebia.com