β-thalassemia is a genetic anemia caused by partial or complete loss of β-globin synthesis leading to ineffective erythropoiesis and RBCs with short life-span. Currently, there is no efficacious oral medication modifying anemia for patients with beta-thalassemia. The inappropriately low levels of the iron regulatory hormone hepcidin enable excessive iron absorption by ferroportin, the unique cellular iron exporter in mammals, leading to organ iron overload and associated morbidities. Correction of unbalanced iron absorption and recycling by induction of hepcidin synthesis or treatment with hepcidin mimetics ameliorates β-thalassemia. However, hepcidin modulation or replacement strategies currently in clinical development all require parenteral drug administration. We identified oral ferroportin inhibitors by screening a library of small molecular weight compounds for modulators of ferroportin internalization. Restricting iron availability by VIT-2763, the first clinical stage oral ferroportin inhibitor, ameliorated anemia and the dysregulated iron homeostasis in the Hbb<sup>th3/+</sup> mouse model of beta-thalassemia intermedia. VIT-2763 not only improved erythropoiesis but also corrected the proportions of myeloid precursors in spleens of Hbb<sup>th3/+</sup> mice. VIT-2763 is currently developed as an oral drug targeting ferroportin for the treatment of β-thalassemia.
Title
Oral ferroportin inhibitor ameliorates ineffective erythropoiesis in a model of β-thalassemia

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All authors are employees of Vifor (International) Ltd. and might own equities. VM and FD are inventors in patents related to the publication.
Abstract

β-thalassemia is a genetic anemia caused by partial or complete loss of β-globin synthesis leading to ineffective erythropoiesis and RBCs with short life-span. Currently, there is no efficacious oral medication modifying anemia for patients with β-thalassemia. The inappropriately low levels of the iron regulatory hormone hepcidin enable excessive iron absorption by ferroportin, the unique cellular iron exporter in mammals, leading to organ iron overload and associated morbidities. Correction of unbalanced iron absorption and recycling by induction of hepcidin synthesis or treatment with hepcidin mimetics ameliorates β-thalassemia. However, hepcidin modulation or replacement strategies currently in clinical development all require parenteral drug administration. We identified oral ferroportin inhibitors by screening a library of small molecular weight compounds for modulators of ferroportin internalization. Restricting iron availability by VIT-2763, the first clinical stage oral ferroportin inhibitor, ameliorated anemia and the dysregulated iron homeostasis in the Hbb^th^3/* mouse model of β-thalassemia intermedia. VIT-2763 not only improved erythropoiesis but also corrected the proportions of myeloid precursors in spleens of Hbb^th^3/* mice. VIT-2763 is currently developed as an oral drug targeting ferroportin for the treatment of β-thalassemia.
36 **Introduction**

β-thalassemia is an inherited anemia caused by mutations in the β-globin gene of hemoglobin (Hb) resulting in abnormal RBCs with decreased lifespan (1, 2). In healthy subjects, Hb is composed of α- and β-globin chains which, together with the iron-containing heme groups, form functional α₂β₂ heterotetramers within RBCs to efficiently deliver oxygen to tissues. The main pathophysiological mechanism in β-thalassemia results from the decreased synthesis of β-globin chains causing accumulation of unpaired α-globin aggregates on the membranes of RBCs. Precipitated α-globin aggregates contain heme and iron which generate ROS leading to a shortened lifespan of RBCs, anemia and tissue hypoxia (3, 4). As a compensatory response to the reduced lifespan of RBCs in β-thalassemia patients, erythropoiesis is greatly stimulated leading to increased proliferation and decreased differentiation of erythroid precursors (ineffective erythropoiesis) in bone marrow (BM) and extramedullary sites, such as spleen and liver (5). The ineffective erythropoiesis in β-thalassemia significantly contributes to the anemia and causes iron over-absorption to support the increased iron demand for Hb synthesis leading to organ iron overload. Liver, spleen, heart and pancreas are the tissues commonly affected by iron overload and without therapeutic intervention iron overload may lead to organ damage, such as liver cirrhosis, heart failure and diabetes. The homeostatic regulation of iron absorption and distribution is controlled by hepcidin, a 25 aa peptide produced mainly in the liver (6). Hepcidin inhibits ferroportin (SLC40A1), the only known cellular iron exporter (7, 8). Ferroportin on the basolateral membrane of intestinal enterocytes transfers dietary iron into the plasma; on spleen and liver macrophages, it exports recycled iron from the Hb of senescent RBCs, and ferroportin on hepatocytes exports iron from liver stores (9). Recently, Zhang et al. have demonstrated ferroportin is highly abundant on mature RBCs and has an essential role in maintaining systemic iron homeostasis and protecting RBCs from oxidative stress (10, 11). Hepcidin binds to and triggers ferroportin internalization and degradation, which causes a rapid drop in blood iron levels (12). In addition, hepcidin inhibits iron export not only by causing ferroportin endocytosis but also by directly occluding the transporter (13). Hepcidin transcription is downregulated by erythropoiesis, iron deficiency and hypoxia, whereas inflammation and high systemic iron levels lead to hepcidin upregulation (6, 14). The ineffective erythropoiesis in β-thalassemia causes iron over-absorption, due to feedback compensatory response to hypoxia, which suppresses hepcidin (15). Since the abnormally high iron levels that result from the suppression of hepcidin further stimulate erythropoiesis, anemia and iron overload are worsened in a
vicious circle. HIF2α plays a major role in linking erythropoiesis and iron absorption, as HIF2α stimulates both erythropoietin (EPO) production and upregulates expression of the divalent metal transporter 1 (DMT1), duodenal cytochrome B (DCytB) and ferroportin (14, 16). EPO triggers the proliferation of erythroblasts and induces the production of the erythroid factor erythroferrone (ERFE), which in turn suppresses hepcidin (17).

Therefore, correction of unbalanced iron absorption by induction of hepcidin synthesis or supplementation of hepcidin mimetics is an attractive therapeutic approach to normalize the dysregulated iron metabolism in β-thalassemia. Experimental drugs, such as shortened hepcidin-derived peptides containing unnatural amino acids (minihepcidins) or oligonucleotides that increase endogenous hepcidin synthesis by inhibition of Tmprss6, have been shown to correct anemia and decrease iron overload in the Hbb^th3/+ mouse model of β-thalassemia intermedia (18-20). In addition, synthetic human hepcidin (LJPC-401), as well as a hepcidin peptidomimetic (PTG-300) and an anti-sense oligonucleotide targeting Tmprss6 (IONIS-TMPRSS6-LRX) have been tested in phase I clinical studies. Hepcidin modulation or replacement strategies currently in clinical development all require parenteral administration. Orally bioavailable minihepcidins have been shown to lower serum iron in wild-type mice (21). Nevertheless, presently no clinical data for an oral drug targeting ferroportin have been published. Oral drug administration offers advantages over parenteral, such as the ease of administration by patients, in particular children, high degree of flexibility on dosages and formulation, cost-effectiveness, less sterility constraints and risk of infection, injection site reaction and anti-drug antibodies generation. Parenteral administration of drugs usually requires medical attendance, which further increases treatment costs and may negatively affect patient compliance.

The scope of the present publication is to describe the profile and mode of action of the compound VIT-2763, an oral small molecule inhibitor of ferroportin. Based on the promising pre-clinical efficacy and tolerability profile, VIT-2763 has entered clinical development (22). Since no oral ferroportin inhibitors or hepcidin-mimetic drugs are available for the treatment of iron overload and ineffective erythropoiesis, VIT-2763 is considered the first oral drug candidate to reach the clinical development stage.
Results

*Ferroportin inhibitors were discovered by screening a small molecule library*

Ferroportin inhibitors were identified by screening a library of small molecular weight compounds (250'000) for modulators of ferroportin internalization using Madin-Darby Canine Kidney (MDCK) cells expressing fluorescently tagged human ferroportin. Confirmed hit compounds were then tested for their ability to inhibit binding and internalization of fluorescently labeled hepcidin (6-carboxytetramethylrhodamine hepcidin, TMR-hepcidin) in the mouse macrophage cell line J774 that expresses endogenous ferroportin. In addition, a fluorescence polarization binding assay was used to more directly demonstrate inhibition of TMR-hepcidin binding to purified recombinant human ferroportin. Compounds that showed inhibition of TMR-hepcidin binding to ferroportin were further profiled with functional assays, including ferroportin internalization and iron efflux assays (Fig. 1A). Lead structures were optimized for potency, drug metabolism and pharmacokinetics parameters by medicinal chemistry and selected compounds were tested for acute efficacy in inducing hypoferremia in C57BL/6 mice. Finally, a small number of pre-clinical candidates were tested for efficacy in the Hbb\(^{th3+/+}\) mouse model of \(\beta\)-thalassemia intermedia (Figure 1A).

**VIT-2763 inhibits hepcidin binding to ferroportin and blocks iron efflux**

Potencies of ferroportin binding were compared between VIT-2763 and hepcidin in a competition assay using the macrophage cell line J774 in which expression of ferroportin can be triggered with iron. The small molecule VIT-2763 competed for binding and internalization of fluorescently labeled TMR-hepcidin with IC\(_{50}\) of 9\(\pm\)5 nM, mean\(\pm\)SD, which was within the range of the potency of unlabeled synthetic hepcidin (IC\(_{50}\) = 13\(\pm\)4 nM, mean\(\pm\)SD) in the same assay (Figure 2A and B).

To investigate the potency of VIT-2763 in a cell-free assay without interference of ferroportin internalization, we used purified human ferroportin expressed in yeast in a fluorescence polarization assay. The binding of TMR-hepcidin to ferroportin leads to increased fluorescence polarization of the TMR-hepcidin ligand. Addition of VIT-2763 dose-dependently reduced the fluorescence polarization signal, indicating that VIT-2763 displaces TMR-hepcidin from ferroportin (Figure 2C, IC\(_{50}\) of 24\(\pm\)13 nM, mean\(\pm\)SD). The binding of TMR-hepcidin to ferroportin was dose-dependently inhibited by unlabeled full-length human hepcidin (Hepcidin-25), although with a lower potency compared to VIT-2763 (Figure 2C, IC\(_{50}\) of 533\(\pm\)250 nM,
mean±SD). A truncated inactive version of hepcidin (Hepcidin-20), lacking the first five N-terminal amino acids involved in ferroportin binding, (23) failed to decrease the fluorescence polarization signal (Supplemental Figure 1). Furthermore, the potency of structurally related ferroportin inhibitors measured in J774 TMR-hepcidin internalization assay correlated significantly with the potency of the same compounds measured in the fluorescence polarization assay (Supplemental Figure 2). Based on these data we concluded that the purified ferroportin shows ligand binding properties similar to the native ferroportin expressed on the cell membrane.

The results with both TMR-hepcidin assays showed that VIT-2763 competes with hepcidin for ferroportin binding and internalization, however these assays do not provide functional information for the effect of VIT-2763 on iron export activity of ferroportin. To address the effect of VIT-2763 on ferroportin function, the human breast cancer cell line T47D expressing endogenous ferroportin was incubated with iron sulfate labeled with the stable isotope $^{58}$Fe for 20h and cells were treated with either VIT-2763 or hepcidin alone or both compounds added simultaneously. Hepcidin blocked the cellular iron efflux dose-dependently, as measured by quantification of $^{58}$Fe in the cell supernatant, with an average EC$_{50}$ of 123±46 nM, mean±SD. Importantly, VIT-2763 inhibited the iron efflux with a slightly higher potency than hepcidin (EC$_{50}$ of 68±21 nM, mean±SD). No additive effect was observed by pre-incubation (not shown) of either VIT-2763 or hepcidin or by co-incubation of both at equimolar concentrations (Figure 2D).

To investigate whether the observed inhibition of cellular iron export by VIT-2763 is dependent on ferroportin, we used HEK293 cells expressing a doxycycline-inducible human ferroportin fused to GFP. In addition, this cell line contains the promoter and adjacent 5' untranslated region with the iron regulatory element (IRE) of the human ferritin H gene fused to a β-lactamase (BLA) reporter gene which is activated by rising intracellular iron levels. Treatment of these cells with doxycycline and VIT-2763 induced the BLA reporter gene activity with an average EC$_{50}$ of 140±50 nM, mean±SD, as a consequence of increasing intracellular iron concentrations caused by blocked iron export (Figure 2E). However, the potency of hepcidin in this iron retention assay was higher with an EC$_{50}$ of 39±20 nM, mean±SD, (Figure 2F). The effects of VIT-2763 and hepcidin were dependent of ferroportin as shown by lack of activity when ferroportin was not induced by doxycycline addition.

In conclusion, the small molecule VIT-2763 inhibited binding of hepcidin to ferroportin, thereby preventing the internalization of fluorescently labeled hepcidin. Importantly, VIT-2763 inhibited the cellular iron efflux in
ferroportin in a ferroportin-dependent manner and with potency comparable to hepcidin, the physiological peptide ligand of ferroportin.

**VIT-2763 triggers ubiquitination and subsequent internalization and degradation of ferroportin**

The generally accepted mechanism by which hepcidin regulates cellular iron export is that hepcidin binds to ferroportin, triggering its ubiquitination, internalization and degradation thereby blocking the iron export activity of ferroportin indirectly by targeting ferroportin for degradation (6, 24, 25). More recently, structural and mutational analyses of a bacterial ferroportin homologue (26) and mammalian ferroportin (13), suggested that hepcidin may inhibit ferroportin directly by occlusion in the absence of ferroportin endocytosis and degradation. We hypothesized that VIT-2763, despite being structurally unrelated, mimics the function of the hepcidin peptide. The TMR-hepcidin assay, in J774 cells described above does not distinguish binding to ferroportin vs. internalization of ferroportin. To study the mechanism of action of VIT-2763 we employed two approaches: i) Ferroportin internalization assay with MDCK cells expressing human ferroportin with a fluorescent HaloTag; ii) Immunoprecipitation studies to assess ferroportin ubiquitination in J774 cells expressing endogenous ferroportin.

MDCK cells constitutively expressing human ferroportin fused to a HaloTag which allows labeling with the fluorescent TMR-HaloTag ligand were treated with either VIT-2763 or hepcidin for 20 min, 1h, 3h, 6h and 18h (Figure 3A). Hepcidin treatment for 18h induced dose-dependent internalization of ferroportin in MDCK cells, as detected by disappearance of surface TMR signal by fluorescence microscopy (Figure 3B). The potency of hepcidin in the MDCK assay was higher than the potency of VIT-2763 (long term average: hepcidin EC\textsubscript{50}=1.5±0.9 nM; VIT-2763 EC\textsubscript{50}=14.4±8.1 nM, mean±SD). Interestingly, the maximal response of VIT-2763 (curve span) was in average 21% lower than the response of hepcidin, suggesting that the ferroportin internalization triggered by VIT-2763 was not complete (Figure 3A-B).

The kinetic effects of hepcidin and VIT-2763 on ferroportin expression were compared using concentrations resulting in a maximal effect for each molecule. Hepcidin (1 μM) triggered ferroportin internalization and formation of intracellular vesicles starting at 20 min, increasing at 1h and resulting in a complete ferroportin internalization from the plasma membrane at 3h and degradation by 3 to 6h (Figure 3A-C). Remarkably, the small molecule VIT-2763 (20 μM) also induced ferroportin internalization, although with slower kinetics and incomplete disappearance of ferroportin from the plasma membrane, even after compound exposure for 18h (Figure 3A-C). Interestingly, VIT-2763 caused a less prominent formation of intracellular ferroportin-
containing vesicles, as compared to hepcidin, which might indicate distinct mechanisms of ferroportin trafficking and degradation (Figure 3A). Competition experiments using VIT-2763 at a constant concentration (1 µM) and increasing concentrations of unlabeled hepcidin (4nM - 4 µM) in the MDCK cells expressing fluorescent ferroportin revealed a shift of the hepcidin dose-response curve to higher EC$_{50}$ values as compared to hepcidin dose-response curve in the absence of the ferroportin inhibitor. This behavior strongly indicated that VIT-2763 competed with hepcidin for ferroportin internalization (Supplemental Figure 3, EC$_{50}$ (hepcidin alone) = 1.6 nM; EC$_{50}$ (VIT-2763 + hepcidin) = 356 nM). These data together with the fluorescence polarization results shown in Figure 2C suggested that VIT-2763 competes with hepcidin for ferroportin binding and internalization.

Immunoprecipitation studies performed using J774 cells expressing endogenous ferroportin showed that both VIT-2763 and hepcidin triggered ubiquitination and degradation of ferroportin. Treatment of J774 cells with hepcidin or VIT-2763 led to a rapid ubiquitination of ferroportin within 10 to 20 minutes (Figure 3D, upper panel) and degradation of ferroportin starting at 40 to 120 min (Figure 3D, lower panel). However, hepcidin induced almost full disappearance of the ferroportin signal, whereas VIT-2763 treatment for 120 min resulted in incomplete ferroportin degradation. In addition, hepcidin induced ferroportin ubiquitination products with higher molecular weight (~100 kDa) compared to VIT-2763 (~70 kDa), suggesting a different degree of ubiquitination (4-5 vs. 1-2 ubiquitin molecules per ferroportin, resp.).

The immunoprecipitation experiments in J774 cells suggested that both VIT-2763 and hepcidin utilize similar pathways of ferroportin internalization and degradation. Nevertheless, slight differences in efficacy and kinetics were demonstrated, which is in agreement with the slower kinetics and less complete degradation of ferroportin in MDCK cells expressing fluorescently labeled human ferroportin.

**VIT-2763 reduced serum iron levels in rodents**

To investigate the in vivo bioavailability and biological activity of VIT-2763 we determined its pharmacokinetic (PK) and pharmacodynamic (PD) properties after single i.v. (1 mg/kg, not shown) or oral (30 mg/kg) administration in male Sprague Dawley rats (Figure 4A). Orally dosed VIT-2763 showed a moderate half-life of 2.0±0.8 hours (mean±SD) and good bioavailability of 48.3± 9.9 % (mean±SD) in rats. Injection of synthetic hepcidin in mice has been shown to decrease plasma iron levels, consistent with a blockade of iron absorption and iron export from tissue stores and from macrophages involved in iron recycling (12). Plasma iron was measured as a marker for PD activity of VIT-2763 in vivo. Plasma iron in
rats dosed orally with VIT-2763 decreased over time, reaching minimal levels 4 hours after oral dosing and recovering within 8-24 hours. Interestingly, plasma iron levels at 24 hours were higher than at baseline (5 min post dose), most likely due to a regulatory feedback response to hypoferremia (Figure 4A).

To compare the efficacy of hepcidin and VIT-2763 in vivo, an acute model of hypoferremia in C57BL/6 mice was used. Intraperitoneal injection of synthetic human hepcidin (5 mg/kg) into mice resulted in a significant reduction of serum iron levels at 1h, 3h and 6h (32%, 59% and 34% lower than the vehicle, resp., Figure 4B). VIT-2763 dosed orally at 60 mg/kg rapidly decreased serum iron at 1h and 3h to comparable levels as hepcidin (40% and 58% lower than the vehicle), demonstrating similar effects of VIT-2763 and hepcidin in C57BL/6 mice from 1h to 3h post dosing (Figure 4B and C). Serum iron levels in mice treated with VIT-2763 for 6h did not change significantly compared to the vehicle group. Both, hepcidin and VIT-2763 had no effect on serum iron levels at 16h post dose.

**VIT-2763 decreased iron overload in the Hbb\(^{th3/+}\) mouse model of \(\beta\)-thalassemia intermedia**

Parenteral administration of agents that induce the synthesis of endogenous hepcidin or modified hepcidin peptides has been shown to correct the ineffective erythopoiesis and to ameliorate iron overload in the Hbb\(^{th3/+}\) model of \(\beta\)-thalassemia intermedia (18-20). Based on the similar mode of action of VIT-2763 and hepcidin in cell-based and biophysical assays, as well as acute efficacy in wild-type rodents, we hypothesized that VIT-2763 might improve the pathophysiological parameters in Hbb\(^{th3/+}\) model of \(\beta\)-thalassemia intermedia and provide a pre-clinical proof of concept for development of oral ferroportin inhibitor for therapy of \(\beta\)-thalassemia.

Hbb\(^{th3/+}\) mice absorb excessive amounts of iron as a consequence of inadequately low hepcidin levels relative to the high iron content in liver, spleen and kidney and increased ferroportin expression in the duodenum (27). To investigate the efficacy of VIT-2763 in the Hbb\(^{th3/+}\) model, mice were fed a diet with a low amount of iron (<10 mg/kg) and dosed orally with either 30 or 100 mg/kg VIT-2763 or vehicle twice daily (bid) for 36 days. In between compound doses, mice had access to drinking water containing the stable iron isotope \(^{58}\)Fe, which allowed differentiating iron absorbed during and before the study. Treatment of Hbb\(^{th3/+}\) mice with 30 or 100 mg/kg VIT-2763 significantly decreased serum iron levels by 77% and 84%, relative to the vehicle Hbb\(^{th3/+}\) group, respectively (Figure 5A), demonstrating the acute effect of the compound on systemic iron. As expected, by blocking ferroportin on liver macrophages and hepatocytes, VIT-2763 did not
change the total liver iron. However, VIT-2763 very efficiently prevented additional liver iron loading during the study, as shown by a dose-dependent reduction of $^{58}$Fe concentration in liver (Figure 5B and C).

The ineffective erythropoiesis in Hbb$^{th3/+}$ mice causes excessive proliferation of erythroid precursors and expansion of the red pulp in the spleen, leading to splenomegaly. Treatment of Hbb$^{th3/+}$ mice with VIT-2763 resulted in a significant reduction of the relative spleen weight by 52% and 65% of the Hbb$^{th3/+}$ vehicle control for 30 and 100 mg/kg VIT-2763, resp., (Figure 5D). Furthermore, Hbb$^{th3/+}$ mice receiving VIT-2763 showed improved distribution of spleen red and white pulp compartments and had a less diffuse iron-staining pattern compared to Hbb$^{th3/+}$ mice treated with vehicle (Figure 5F). These results highlight the potential of the oral ferroportin inhibitor to attenuate excessive extramedullary erythropoiesis in spleen. The concentration of spleen iron increased dose-dependently (not shown), consistent with the decrease in the spleen weight and retention of iron in spleen macrophages, however, the total spleen iron content remained unchanged in the group treated with 30 mg/kg and decreased significantly in mice treated with 100 mg/kg compound (Figure 5E).

**VIT-2763 ameliorated anemia and improved ineffective erythropoiesis in Hbb$^{th3/+}$ mice**

Notably, ferroportin inhibition with the oral drug VIT-2763 not only decreased plasma and organ iron levels but also improved the hematological parameters in Hbb$^{th3/+}$ mice. VIT-2763 significantly increased Hb levels (as of day 8 of treatment, Figure 6A), RBC counts (Figure 6B), mean corpuscular hemoglobin concentration (MCHC, Figure 6C) and significantly lowered reticulocyte counts (Figure 6D), mean corpuscular hemoglobin (MCH, Figure 6E), mean corpuscular volume (MCV, Figure 6F) and RBC distribution width (RDW, Figure 6G) in Hbb$^{th3/+}$ mice, as compared to the Hbb$^{th3/+}$ vehicle group. Therefore, ferroportin inhibition by VIT-2763 significantly ameliorated anemia and corrected pathologically altered RBCs and reticulocyte counts, indicating improved erythropoiesis in Hbb$^{th3/+}$ mice. Remarkably, dietary iron restriction of Hbb$^{th3/+}$ mice for the duration of the study failed to lower serum iron and improve anemia (data not shown), demonstrating that iron restriction by pharmacological inhibition of ferroportin is necessary for a substantial therapeutic effect.

The central pathophysiological mechanism in β-thalassemia is ineffective erythropoiesis, which is characterized by increased proliferation and decreased differentiation of erythroid progenitors in hematopoietic organs. As a result of the α/β globin imbalance, RBCs accumulate toxic membrane α-globin aggregates and produce excessive ROS. The effect of VIT-2763 on erythropoiesis was studied by
analyzing the percentage of differentiating erythroid precursors in BM and spleen based on Ter119 and CD44 markers. VIT-2763 reduced the percentages of the early erythroid precursors proerythroblasts (Figure 7A and D, gate 1), basophilic (Figure 7A and D, gate 2), and polychromatic erythroblasts (Figure 7A and D, gate 3) in BM and spleen of Hbb<sup>th3/+</sup> mice and increased the percentages of mature erythrocytes (Figure 7A and D, gate 5). The most prominent effect of the compound on erythropoiesis was observed in decreasing polychromatic erythroblasts and in increasing mature erythrocyte populations (gate 3 and 5, resp., Figure 7A, B, D and E). More importantly, significantly lower proportions of mature BM and spleen erythrocytes stained positive for ROS in VIT-2763- compared to vehicle-treated Hbb<sup>th3/+</sup> mice (Figure 7C and F), indicating diminished oxidative damage of erythroid cells. As a result, mature RBC and their precursors in blood of Hbb<sup>th3/+</sup> mice receiving VIT-2763 expressed less phosphatidylserine (PS) indicating reduced apoptosis (Supplemental Figure 4). The increased proportion of mature erythroid cells and decreased oxidative stress in BM and spleens of Hbb<sup>th3/+</sup> mice together with the reduced apoptosis of mature RBC and RBC precursors in blood suggest that VIT-2763 ameliorated the ineffective erythropoiesis in Hbb<sup>th3/+</sup> mice.

**VIT-2763 reduced the formation of α-globin aggregates, extended the lifespan and improved the functional parameters of circulating RBCs in Hbb<sup>th3/+</sup> mice**

To investigate how VIT-2763 improves anemia and iron overload, Hbb<sup>th3/+</sup> mice were treated with the compound for 4-7 weeks and a broader range of biomarkers were investigated in several independent studies.

In β-thalassemia intermedia, the imbalanced synthesis of α- and β-globin chains of Hb leads to formation of insoluble α-globin aggregates containing free heme and iron, causing ROS formation and apoptosis of the late stage erythroid progenitors. Analysis of the membrane-bound globins by Triton Acetic acid Urea (TAU) gel electrophoresis showed a dose-dependent decrease in the levels of toxic α-globin aggregates in RBC membrane preparations from Hbb<sup>th3/+</sup> mice treated with VIT-2763 for 28 days compared to the Hbb<sup>th3/+</sup> vehicle group (Figure 8A). The reduction of the membrane α-globin was significant as early as day 8 of compound treatment (data not shown) and further decreased in the following two weeks, suggesting a rapid improvement of erythropoiesis. The insoluble globin aggregates on RBC membranes contain products of Hb oxidative denaturation, such as metHb, free heme and iron, which all contribute to ROS generation in RBCs (28). In agreement with the reduced α-globin aggregates in RBCs, VIT-2763 decreased the percentage of ROS-positive RBCs in Hbb<sup>th3/+</sup> mice from 67% to 30% (Figure 8B).
Reticulocytes of healthy individuals clear mitochondria by mitophagy during maturation and terminally
differentiated RBCs produce energy by glycolysis (29). However, it has been shown that mitophagy in β-
thalassemia is impaired, resulting in retention of mitochondria in mature RBCs (30, 31). Flow cytometry
analysis of MitoTracker labeled blood cells showed that essentially all reticulocytes from both WT and
Hbb<sup>th3/+</sup> mice contained mitochondria (MitoTracker<sup>+</sup> cells, Figure 9A). Upon maturation, RBCs from WT mice
progressively eliminated their mitochondria, with only 1.5% of terminally differentiated RBCs retaining
mitochondria (Figure 9A and B). Strikingly, 10.3% (group average value) of mature RBCs from the Hbb<sup>th3/+</sup>
vehicle group preserved mitochondria and produced higher levels of ROS compared to RBCs without
mitochondria (ratio of mean fluorescence intensities (MFI) of ROS<sup>pos</sup> MitoTracker<sup>pos</sup> to ROS<sup>pos</sup> MitoTracker<sup>neg</sup>
RBCs = 2.5, group average value, representative dot plot shown in Figure 9A). In Hbb<sup>th3/+</sup> mice VIT-2763
significantly reduced the proportion of mature RBCs containing mitochondria to an average of 4.9% (Figure
9B). Importantly, RBCs devoid of mitochondria produced lower levels of ROS (ROS<sup>pos</sup> MitoTracker<sup>neg</sup>
populations in Figure 9A). These data suggested that at least part of the oxidative stress in RBCs from
Hbb<sup>th3/+</sup> mice is mediated by erythrocytes that failed to eliminate their mitochondria. By improving
erthropoiesis, VIT-2763 indirectly ameliorated mitophagy and decreased the oxidative stress in RBCs of
Hbb<sup>th3/+</sup> mice.

Increased ROS levels in RBCs of Hbb<sup>th3/+</sup> mice cause membrane damage and lead to exposure of PS to the
extracellular space. PS exposure to the outer cell membrane is an apoptotic signal and targets RBCs for
phagocytosis (32). VIT-2763 treatment of Hbb<sup>th3/+</sup> mice significantly decreased PS exposure of RBCs and
precursors of mature erythrocytes, as shown by annexin V staining (Figure 10A and Supplemental Figure
4). PS exposure marks RBCs for phagocytosis by scavenging macrophages which deliver the damaged
RBCs to spleen and liver for degradation (33). The released heme is catabolized by heme oxygenase 1 (HMOX1), which is upregulated in β-thalassemia, due to excessive RBC apoptosis (34). VIT-2763 treatment
significantly reduced the expression of Hmox1 in livers of Hbb<sup>th3/+</sup> mice, most likely as a result of the
decreased RBC turnover (Figure 10B). Indeed, the half-life of RBCs in Hbb<sup>th3/+</sup> mice treated with vehicle
was 8 days and administration of VIT-2763 extended it to 22 days, which was similar to the half-life of RBCs
in WT mice (Figure 10C).
**VIT-2763 ameliorated hypoxia in Hbb$^{th3/+}$ mice**

Hbb$^{th3/+}$ mice are systemically hypoxic as a result of inappropriate tissue oxygenation by the defective RBCs (14, 18). Indeed, flow cytometry analysis of RBCs stained with a fluorescent surrogate marker for hypoxia (Enzo Life Sciences), confirmed a higher MFI signal in Hbb$^{th3/+}$ mice treated with vehicle compared to WT mice (Figure 11A). RBC from Hbb$^{th3/+}$ mice that received VIT-2763 for four weeks showed reduced MFI levels of the fluorogenic hypoxia marker, suggesting improved oxygenation of RBCs (Figure 11A). Hypoxia is in the center of the vicious circle driving iron over-absorption and ineffective erythropoiesis in β-thalassemia by upregulating genes involved in iron uptake and erythropoiesis, such as DMT-1, DcytB, ferroportin and EPO. The effect of VIT-2763 on the hypoxia-sensitive marker in RBC is most likely indirect and mediated by the improved erythropoiesis and increased Hb resulting in a better tissue oxygenation. Consistent with the improvement of tissue oxygenation, Hbb$^{th3/+}$ mice treated with VIT-2763 produced significantly less serum EPO compared to the vehicle group (Figure 11B).

Elevated EPO levels in Hbb$^{th3/+}$ mice upregulated Erfe, an erythroid regulatory hormone known to suppress hepcidin (17). In agreement with reduced serum EPO, Erfe gene expression was significantly lower in spleens of Hbb$^{th3/+}$ mice dosed with VIT-2763 compared to those treated with vehicle alone (Figure 11C). Erfe is produced by erythrocyte precursors proliferating massively in spleens of Hbb$^{th3/+}$ mice as a consequence of extramedullary erythropoiesis. Therefore, the effect of VIT-2763 on Erfe expression in spleen is mediated by reduced numbers of RBC precursors in the spleen.

Liver hepcidin (*Hamp*) expression in Hbb$^{th3/+}$ and WT mice was similar and did not change upon VIT-2763 treatment (Figure 11D), as similarly reported for minihepcidin in Hbb$^{th3/+}$ mice (18).

**Effects of VIT-2763 on myeloid precursors in spleens of Hbb$^{th3/+}$ mice**

It has been previously shown that the proportion of immature myeloid cells is highly increased in spleens of Hbb$^{th3/+}$ mice compared to WT, which suggested that the terminal neutrophil maturation in spleens of Hbb$^{th3/+}$ mice is compromised (35). Flow cytometry analysis of myelopoiesis in spleens confirmed a significant expansion of mature neutrophils (Figure 12A, population i), immature myeloid cells (Figure 12, population ii) and inflammatory monocytes (Figure 12A, population iv) in Hbb$^{th3/+}$ mice. VIT-2763 dosed for three weeks did not change the percentage of resident monocytes (population iii), however VIT-2763 significantly reduced the percentage of mature neutrophils (population i), immature myeloid cells (population ii) and inflammatory monocytes (population iv, Figure 12A and B). These data demonstrated that iron
restriction by the ferroportin inhibitor VIT-2763 results not only in correction of erythropoiesis but also leads

to amelioration of myelopoiesis in spleen. It remains to be investigated whether the quantitative changes in

neutrophil populations also translate to functional improvement, i.e. chemotaxis, opsonization and ROS

production in response to bacterial challenge.
The data in this paper summarize the discovery and pre-clinical efficacy of the oral ferroportin inhibitor VIT-2763. This small molecule drug has a mode of action similar to the peptide hepcidin: in cells, VIT-2763 blocked iron efflux with similar potency to hepcidin, competed with hepcidin for ferroportin binding and triggered ferroportin internalization and ubiquitination. Importantly, VIT-2763 improved the ineffective erythropoiesis, ameliorated anemia and prevented liver iron loading in the Hbb^b3/+ mouse model of β-thalassemia. Presumably, VIT-2763 limits iron availability for formation of toxic α-globin aggregates and ROS in erythroid precursors and thereby improves erythropoiesis. As a result, more RBCs with extended life-span ameliorate anemia and improve tissue oxygenation. VIT-2763 not only improved erythropoiesis but also corrected the proportion of spleen myeloid precursors in Hbb^b3/+ mice. VIT-2763 showed no cytotoxicity in assay detecting cellular ATP levels (IC50 >100 μM). In non-clinical toxicology studies in rodents, the compound was well tolerated with No Observed Adverse Effect Level (NOAEL) above 600 mg/kg in 14-day dosing studies with healthy rodents. In longer-term studies, there has been no dose-limiting toxicity. The dose-limiting effects in healthy rodents are related to the pharmacology of VIT-2763 (restricting iron uptake) and the expected iron deficiency anemia and effects secondary to that. Based on the mode of action described here, VIT-2763 is expected to correct ineffective erythropoiesis and iron overload in a range of diseases, such as hereditary haemochromatosis, hereditary anemias, e.g. thalassemia, sickle cell disease, or myeloproliferative/myelodysplastic disorders, e.g. polycythemia vera and myelodysplastic syndrome (MDS), respectively or other hemoglobinopathies. In a recently concluded phase I study in healthy individuals, VIT-2763 was well tolerated and showed a dose-linear pharmacokinetic profile. Importantly, serum iron was lowered and remained below baseline values up to 24 hours post dose. Following these positive phase I results, Vifor Pharma intends to start a phase II proof-of-concept trial in β-thalassemia patients (22).

All hepcidin-mimetics in clinical development, such as synthetic hepcidin, hepcidin peptidomimetics or agents that increase the production of endogenous hepcidin (siRNA or anti-sense DNA targeting Tmprss6) are injectable drugs with higher molecular weight and no oral bioavailability. PK modeling using monkey plasma revealed that hepcidin has unfavorable pharmacological properties (t1/2<2.5 min) (36) and because of its four disulfide bonds is particularly difficult to synthesize. Activin receptor ligand traps, such as sotatercept and luspatercept are clinical stage biologics that modify late-stage erythrocyte precursor cell
differentiation and maturation (37). The longer half-life of these parenteral biologics offers the advantage of less frequent administration (once every 3 weeks) compared to an oral drug. However, the extended lifespan might become a disadvantage in case of potential safety concerns. Indeed, the molecular target(s) of activin receptor traps are not well characterized and reducing the activity of both known activin receptor ligands, GDF8 and GDF11, has been associated with increased risk of cardiovascular events (38).

Therefore, VIT-2763 is anticipated to be the first oral ferroportin inhibitor in clinical development with a well-defined target profile and offering important advantages of small molecules over parenteral medicines. Ferroportin inhibitors are a class of structurally related small molecules that have been identified and optimized based on their potency to inhibit binding and internalization of fluorescent hepcidin (TMR-hepcidin) in J774 cell expressing endogenous ferroportin. In addition, the internalization assay using MDCK cells expressing human ferroportin revealed VIT-2763 induced ferroportin internalization similarly to hepcidin, although with slower kinetics and smaller maximal response. Interestingly, the initial hits identified in the library by the TMR-hepcidin ferroportin binding assay in J774 cells, essentially lacked ferroportin internalization activity in MDCK ferroportin internalization assay (data not shown), suggesting potency of compounds above a certain threshold in ferroportin binding assay is necessary for detectable ferroportin internalization activity and confirming the appropriate choice of the screening strategy depicted in Figure 1A.

VIT-2763 showed similar or higher potency in binding and iron efflux assays as hepcidin, however the compound had about a tenfold lower potency in the ferroportin internalization assay in MDCK cells. One possibility is VIT-2763 blocks directly iron export by occluding ferroportin, similar to what has been shown for hepcidin (13). The incomplete ferroportin degradation observed in MDCK cells even after 18h exposure to VIT-2763 might be suggestive of the occlusion mode of action. Cells expressing endocytosis-deficient ferroportin or RBCs, which lack endocytosis machinery, will be helpful to experimentally address the ability of VIT-2763 to occlude ferroportin. Interestingly, hepcidin triggered formation of detectable intracellular vesicles in MDCK cells, which were less pronounced in VIT-2763-treated cells. The different pattern of the intracellular vesicles in MDCK cells triggered by VIT-2763 might reflect distinct pathways of ferroportin degradation.

Immunoprecipitation studies in J774 cells showed that the small molecule VIT-2763 also triggered rapid ubiquitination of endogenous ferroportin, as previously shown for hepcidin (24). It remains to be studied...
whether the different degree of ubiquitination of ferroportin induced by hepcidin and VIT-2763 targets ferroportin to different endocytic pathways. We have investigated the effect of VIT-2763 in duodenum, spleen and liver by Western blot and qPCR from Hbb$^{th3/4}$ and WT mice. VIT-2763 did not reduce ferroportin levels in these tissues, as previously shown for minihepcidins (13), despite significantly decreasing serum iron (data not shown). The absence of ferroportin degradation, together with the reduction of serum iron by VIT-2763 is consistent with the mechanism of ferroportin occlusion. The reasons for the differential effect of hepcidin agonists on ferroportin endocytosis in cells and tissues are not clear. One possibility, discussed by Aschemeyer. et al. is different glycosylation of ferroportin and/or ferroportin-interacting proteins in cell lines versus tissues, which may differentially affect agonist binding to ferroportin and endocytosis pathways. Alternatively, the lack of degradation of ferroportin in spleen lysates could be due to analysis of the total membrane fraction (including plasma membrane and endosomes) by Western blot.

VIT-2763 is systemically available and most likely blocks iron export in all ferroportin-expressing tissues, including duodenum, spleen and liver. Recent publications showed that ferroportin is highly abundant in mature RBCs and contributes a significant amount of iron to the blood (10, 11). It is therefore plausible that erythroid ferroportin inhibition by VIT-2763 contributes to the fast reduction of systemic iron observed in rodents. We are currently addressing the effect of VIT-2763 on RBCs.

Our data showed VIT-2763 ameliorated anemia, improved erythropoiesis and decreased organ iron loading in the Hbb$^{th3/4}$ $\beta$-thalassemia intermedia disease model. Presumably, iron restriction by VIT-2763 slows down the formation of Hb in developing erythroid cells, leading to reduction of toxic $\alpha$-globin aggregates in erythrocytes and associated oxidative stress. Similarly, induction of endogenous hepcidin by Tmprss6-targeting oligonucleotides or injection of hepcidin mimetics, such as minihepcidin in the Hbb$^{th3/4}$ model resulted in decreased $\alpha$-globin aggregates in membranes of RBCs (18-20). Hb assembly is assisted by the molecular chaperone $\alpha$-hemoglobin stabilizing protein (AHSP) which specifically binds to free $\alpha$-globin chains, before they associate with $\beta$-globin chains, and prevents their aggregation (39). However in $\beta$-thalassemia, excess $\alpha$-globin chains exceed the capacity of AHSP and the unstable free $\alpha$-globin molecules undergo auto-oxidation and generate ROS that initiates a cascade of events leading to hemolysis and ineffective erythropoiesis (40). In addition, genetic evidence in patients supports the idea that reduction in $\alpha$-globin chain, due to co-inherited $\alpha$-thalassemia, is beneficial in patients with $\beta$-thalassemia (3).
molecular mechanism of how iron restriction by ferroportin inhibition improves symptoms in β-thalassemia disease models needs further investigation.

VIT-2763 dose-dependently decreased MCH, as shown previously for hepcidin and hepcidin agonists in the Hbb\textsuperscript{th3/+} model (20, 27). These data indicate that iron restriction by VIT-2763 is reducing the erythroid iron intake per cell, resulting in lower MCH, but increasing the number of RBCs thereby improving the anemia (total Hb is increased). Overall, the decrease in MCH and MCV is associated with beneficial effects in the thalassemia model. Therefore, dose-finding clinical studies with VIT-2763 will allow avoidance of excessive iron restriction and preserve a stable number of RBCs by tightly monitoring of hematological indices, such as MCH, MCV and RBC counts. The moderate half-life of VIT-2763 in plasma and the high degree of flexibility on dosing provide important advantages in finely tuning the dose for optimal iron restriction effect.

One important consequence of iron restriction by VIT-2763 is the decreased formation of ROS in developing erythroblasts in BM and spleen, as well as in RBCs of Hbb\textsuperscript{th3/+} mice. Interestingly, 10-15% of mature RBCs in Hbb\textsuperscript{th3/+} mice have mitochondria, which are absent in WT RBCs. Similar abnormal retention of mitochondria in mature RBCs has been reported in patients and mice with sickle cell disease (41). Moreover, RBCs with mitochondria produced excessive levels of ROS. In healthy individuals, mitochondria disappear from RBCs during development as an adaptation to avoid generation of ROS (42). Notably, RBCs of Hbb\textsuperscript{th3/+} mice receiving VIT-2763 significantly reduced the proportion of mature RBCs containing mitochondria and producing elevated ROS, indicating improved terminal differentiation. To our knowledge, the effect of VIT-2763 on mitochondria in the Hbb\textsuperscript{th3/+} model has not been reported for other drugs targeting β-thalassemia.

VIT-2763 normalized myeloid spleen cell composition, most likely as a consequence of the corrected extramedullary erythropoiesis by VIT-2763. The ability of VIT-2763 to correct the proportion of spleen myeloid cells in the Hbb\textsuperscript{th3/+} model indicates a potential for decreasing inflammation in β-thalassemia. This effect has not been reported for other drugs targeting β-thalassemia.

Patients with non-transfusion dependent β-thalassemia (NTDT) have a moderate anemia but still develop iron overload due to the ineffective erythropoiesis and inadequate hepcidin production. The most severe form of β-thalassemia, transfusion dependent β-thalassemia (TDT), requires regular blood transfusions (more than 5 RBC transfusions in 24 weeks) leading to secondary iron overload requiring iron chelation.
therapy (43). Blood transfusions and iron chelation therapy do not address the underlying pathological mechanism of the disease and are associated with increased risk of infection and adverse reactions. The remarkable efficacy of VIT-2763 in Hbb<sub>th3/+</sub> mice and the good tolerability profile in the non-clinical safety studies provide a direct rationale for investigating the efficacy of VIT-2763 in NTDT. VIT-2763 has not yet been tested in a mouse model of TDT. However, based on the mode of action of the compound, beneficial effects may be expected. Patients with TDT have severe iron overload due to regular blood transfusions. Blood transfusion causes a transient upregulation of hepcidin, which returns to basal values when the Hb levels decrease (44). Prevention of intestinal iron absorption by VIT-2763 during the intervals between transfusions might help to reduce further iron loading in TDT patients. More importantly, blood transfusion generates non-transferrin bound iron (NTBI) which is released by macrophages recycling damaged RBCs and triggers oxidative stress and vascular damage (45). Moreover, thalassemia patients on regular blood transfusions and chelation had elevated NTBI levels which correlated to the presence of heart disease (46). The oral ferroportin inhibitor VIT-2763 might prevent these noxious effects by sequestrating iron in macrophages and therefore interrupting a vicious cycle in β-thalassemia. Scavenging NTBI by apo-transferrin treatment was found to attenuate transfusion mediated increases in plasma NTBI and associated excess tissue iron loading (47, 48). Nevertheless, testing the efficacy of VIT-2763 in a TDT disease model will help to address this hypothesis.

In summary, by inhibiting ferroportin and thereby limiting the availability of iron to erythroid precursors, VIT-2763 decreases the formation of α-globin aggregates generating ROS and improves the efficiency of erythropoiesis. In turn, the resulting RBCs with increased Hb supply more oxygen to tissues which suppresses the hypoxia response and normalizes iron absorption. The clinical development of the oral ferroportin inhibitor has the potential to provide a therapeutic option with dosing convenience for patients with β-thalassemia and other diseases with dysregulated iron homeostasis.
Materials and methods

TMR-Hepcidin internalization assay in J774 cells

J774 cells (DSMZ), harvested from 80% confluent cultures, were plated at 8x10^5 cells/ml in complete DMEM medium supplemented with FBS, Penicillin-Streptomycin (Gibco), 200, (Fe(III)-chloride and Nitrilotriacetic acid, Sigma-Aldrich), in 96-well MicroClear plates (Greiner) and grown at 37°C. After overnight incubation, cells were washed and serial dilutions of test compounds were added in triplicates.

J774 cells were pre-incubated with compounds for 15 minutes before addition of TMR-hepcidin (kindly provided by S. Bansal, King’s College London) at 25 nM. Cells were incubated for two hours and Hoechst 33342 dye (Thermo Fisher Scientific) was added to a final concentration of 0.5 µg/ml. Cells were washed with Dulbecco’s PBS (DPBS, Gibco) and fixed using 5.3% paraformaldehyde (Electron Microscopy Sciences) for 15 minutes. TMR (530-550 nm excitation / 575-625 nm emission / 250 ms exposure time) and Hoechst 33342 fluorescence images were acquired using a ScanR plate imager (Olympus) with a 20x high NA objective. Four pictures were acquired per well and fluorescence channel covering 1500 cells/well. The acquired data were analyzed with ScanR image analysis software. Image analysis included detection of nuclei, identification of cell-associated regions, application of a virtual channel and thresholding for rolling-ball-type background reduction, followed by application of the Sum(Mean) algorithm to measure the TMR fluorescence associated with cells as a quantitative measure for internalized TMR-hepcidin.

Fluorescence polarization assay with recombinant human ferroportin and TMR-hepcidin

A mixture of 1.95 µM human recombinant ferroportin isolated from Pichia pastoris yeast cells expressing human ferroportin with a C-terminal FLAG affinity tag (49) and 30 nM TMR-hepcidin in FP assay buffer containing 50 mM Tris-HCl pH 7.3, 200 mM NaCl (Sigma Aldrich), 0.02% DDM (n-Dodecyl-β-D-maltopyranoside, D310S, Sol-Grade 98% pure, Anatrace), 0.1% BSA (Sigma Aldrich) was plated into a 384-well black low volume round bottom plate (Corning) at 16 µl per well. A volume of 8 µl of serial dilutions of test compounds were added in duplicates to reach final ferroportin and TMR-hepcidin concentrations of 0.65 µM and 10 nM, respectively. Plates were incubated for 90 minutes at room temperature and parallel (Fpara) and perpendicular (Fperp) fluorescence was measured in a Synergy H1 fluorescence reader (BioTek). FP values were calculated in mP according to the formula mP = ((Fpara-Fperp)/(Fpara+Fperp))x1000.
Iron efflux assay in T47D cells

Human T47D (ECACC) epithelial breast cancer cells were plated in 24-well plates (Greiner) at 350,000 cells/well and incubated overnight with 100 μM 56Fe(II) sulfate, (Vifor (International) Ltd.) in 500 μM L-Ascorbic Acid (Sigma Aldrich) containing DMEM growth medium. T47D cells were washed once with 500 μl iron uptake buffer (IUB; PIPES 20 mM, Glucose Monohydrate 5 mM, NaCl 130 mM, KCl 10 mM, MgSO4 1 mM), then once with iron removal buffer (100 μM bathophenanthroline disulfonic acid disodium salt trihydrate and 500 μM Na2S2O4 in IUB, Sigma Aldrich) and again twice with IUB. Serial dilutions of hepcidin or VIT-2763 were added to each well in a total volume of 0.6 ml. Cells were incubated in growth medium without FBS at 37°C for 20h. 56Fe was measured using inductively coupled plasma mass spectrometry (ICP-MS, Thermo Scientific, Element 2). Results are plotted as ng 56Fe in supernatant per mg protein in cell lysates.

Ferritin-BLA reporter assay in HEK-FPN1-GFP cells

The HEK-FPN1-GFP ferritin-BLA cell clone was generated by stable integration of (i) a human FPN1-GFP fusion construct inserted into a derivative of the doxycycline-inducible pTRE-Tight-BI plasmid (Clontech) and (ii) a human ferritin promoter-BLA reporter gene into a derivative of the HEK-293 Tet-ON Advanced cell line (Clontech). To generate the ferritin-BLA reporter gene construct, a 1.4 kb fragment of the human ferretin H promoter was amplified by PCR from human genomic DNA (forward primer 5'-CAGGTTTGTGACATCCTGAA-3'; reverse primer 5'-GGCGGCGACTAAGGAGG-3') and inserted in front of the BLA gene present in the pcDNA™6.2/cGHFP-BLazer™-DEST plasmid (Thermo Fisher) thereby replacing the original CMV promoter and placing the Iron Response Element (IRE) that regulates translation of the ferritin gene ca. 170 bp upstream of the start codon of the BLA reporter gene. HEK-BLA cells were seeded at 1.8x10⁵ cells/ml in DMEM/F12 containing 10% FBS (Clontech), 1% Penicillin-Streptomycin, 200 μg/ml Hygromycin B, Blasticidin 5 μg/ml, (Thermo Fisher Scientific) and 4 μg/ml doxycycline (Clontech) in 384-well poly-D-lysine coated microplates. Dilution series of the test compound was added in quadruplicates and plates were incubated overnight at 37°C. Cells were washed three times with HBSS. BLA activity was detected by adding the GeneBlazer reagent CCF4-AM (Thermo Fisher Scientific) to the cells. After incubation of the plates at 18°C for 60 minutes in darkness, blue and green fluorescence signals were measured in a Safire2 fluorescence plate reader (Tecan) with excitation at 410 nm and emissions at 458 nm (blue) and 522 nm (green). The ratio of blue (458 nm) and green (522 nm) fluorescence as a
measure for BLA activity was calculated and EC\textsubscript{50} values were determined with the calculated blue/green fluorescence ratios.

**FPN1-HaloTag-TMR internalization assay in MDCK cells**

The assay quantifies ferroportin internalization triggered by hepcidin or VIT-2763 through microscopic detection of the disappearance of cell surface-associated fluorescently labeled ferroportin in a MDCK cell clone. The MDCK cell clone stably expresses human ferroportin with a C-terminal HaloTag fusion (Promega) and could be covalently labeled with HaloTag TMR-ligand. Cells were plated at 3\times10^5 cells/ml in DMEM medium and grown at 37°C overnight. MDCK cells were stained with 2µM HaloTag TMR-ligand (Promega) in growth medium for 20 min at 37°C, 5% CO\textsubscript{2} in the dark. Cells were then treated with serial dilutions of VIT-2763 or human hepcidin (Bachem) and incubated over night at 37°C. Nuclei were counterstained with 3µM Draq5 (eBioscience), cells were washed twice with DPBS+CaCl\textsubscript{2}+MgCl\textsubscript{2} (BioTek 405 washer) and subsequently fixed with 4% paraformaldehyde in DPBS for 15 min. After three DPBS washes of cells, fluorescence images were acquired using an inverted IX81 epifluorescence microscope (ScanR, Olympus) and a 20X high NA objective. Four pictures were acquired per well for each channel (TMR and CY5) and the acquired data were analyzed using the Columbus image data storage and analysis system (Perkin Elmer). Texture analysis (SER-Ridge) was used to quantify the disappearance of surface ferroportin triggered by hepcidin or VIT-2763, measured by a decrease of edge structures in the TMR channel.

**Immunoprecipitation and Western blot**

J774 cells were seeded at 12\times10^6 cells per Petri dish in complete DMEM medium containing 200 µM Fe(III)-NTA and grown overnight at 37°C. Cells were incubated with human hepcidin (150 nM) or VIT-2763 (100 nM) for 10, 20, 40, 60 or 120 min. Cells were washed and lysed with ice-cold IP lysis buffer (Pierce, Thermo Scientific) including 1X HALT protease inhibitor cocktail (Thermo Scientific) and 10 mM iodoacetamide (Sigma Aldrich) to stabilize ubiquitinated proteins. Immunoprecipitation was done using the Pierce Classic IP Kit (Thermo Scientific) following the manufacturer's protocol. Cell lysate was incubated with the affinity purified rabbit anti-ferroportin antibody MTP-1 (MTP11-A, Alpha Diagnostic International).

After immunoprecipitation samples were analyzed by Western blotting using the affinity purified rabbit anti-mouse F308 antibody raised against a GST fusion protein of mouse ferroportin aa 224-308 (Vifor International) Ltd and a mouse anti-mono- and polyubiquitinylated conjugates monoclonal antibody (Enzo
Life Sciences, BML-PW8810) for detection of ferroportin and ubiquitin, respectively. Mouse monoclonal anti-rabbit IgG light chain (Abcam, ab99697) and anti-mouse IgG H&L (Abcam, ab6789) HRP conjugates were used as secondary antibodies.

**Mouse strains, housing and compliance with animal protection law**

C57BL/6 mice were purchased from Charles River (Germany). Hb\textsuperscript{th3/+} mice (C57BL/6 background) were purchased from Jackson Laboratory (Stock 002683) (50) and bred under specific pathogen-free conditions in the animal facility of Vifor (International) Ltd., according to the regulations of the Swiss veterinary law.

The facility employs a 12-hour dark/light cycle and all mice were provided water and food ad libitum. Mice were group-housed and maintained on standard rodent diet (Granovit, 250 ppm mg/kg iron content) unless otherwise stated. Individual cages were randomly assigned to the treatment groups for equal distribution of gender and ages. All studies were performed in compliance with the Code of Conduct of Vifor Pharma Group.

**Efficacy of VIT-2763 in Hb\textsuperscript{th3/+} mice**

8-12 week old male and female Hb\textsuperscript{th3/+} mice (n=8 to 13) were treated with either vehicle (0.5% methylcellulose) or VIT-2763 at the indicated doses by oral gavage twice daily for the specified duration.

The dosing was performed in the dark phase of the facility room, corresponding to the active period of rodents. WT littermates dosed with vehicle served as controls. To distinguish iron preloaded in mice at study start from iron acquired during the study period, mice were fed a low iron diet (Granovit, <10 mg/kg iron content) during the study period and the stable iron isotope \textsuperscript{58}Fe was supplemented into the drinking water (1 mM \textsuperscript{58}FeSO\textsubscript{4} with 10 mM ascorbic acid as a reducing agent) during the 6h period between both doses of compound. For the remaining 18h, all animals had access to mineral water without iron. Hb levels were determined weekly in tail vein blood using a Hemocue® Hb 201 device. Animals were sacrificed three hours after the final dose.

**Flow cytometry for ROS, erythropoiesis, myelopoiesis, mitochondria, hypoxia, and PS exposure**

Erythroid cells from BM and spleen were analyzed by flow cytometry. Distinct stages of RBC precursors were identified based on expression levels of Ter119 (APC-conjugated rat anti-mouse Ter119, eBioscience, 17-5921), CD44 (APC-Cy7-conjugated rat anti-mouse CD44, BioLegend, 103028), CD71 (PE-conjugated rat anti-mouse CD71, eBioscience, 12-0711), and the forward scatter (FSC) as a cell size measure (51). ROS in mature RBCs were detected with the indicator CM-H2DCFDA (Invitrogen) after gating on Ter119\textsuperscript{+}.
and CD71 cells. Myelopoiesis was assessed in single spleen cell suspension. Mature neutrophils were identified as CD11b^+ Ly6G^{high}Ly6C^{int}, immature myeloid cells were identified as CD11b^+Ly6G^{int}Ly6C^{int}, inflammatory monocytes were identified as CD11b^+Ly6G^{neg}Ly6C^{high}, and resident monocytes were identified as CD11b^+Ly6G^{neg}Ly6C^{int} using FITC-conjugated rat anti-mouse CD11b, PE-conjugated rat anti-mouse Ly6G and APC-conjugated rat anti-mouse Ly6C (all from eBioscience, 11-0112-82, 12-9668-82 and 17-5932-82, resp.). Mitochondria were detected using MitoTracker Deep Red FM (Invitrogen) in RBCs labelled with Ter119 and CD71 antibodies in a combination with CM-H2DCFDA staining for ROS detection. Intracellular hypoxia was measured using the ROS-ID® Hypoxia/Oxidative stress detection kit (Enzo Life Sciences, ENZ-51042-K500). RBCs were labelled with Ter119 antibody and incubated with the hypoxia detection probe according to the manufacturer’s instructions. PS exposure was detected using the Annexin V Apoptosis Detection Kit (Invitrogen) on peripheral blood cells labelled with Ter119 and CD71 antibodies.

Statistical analysis
For quantification of EC_{50} or IC_{50} in the assays, for each data set the fit of the “log(inhibitor) vs. response (three parameters)” model was compared to the fit of the “log(inhibitor) vs. response – Variable slope (four parameters)” model and the data of the preferred model were used. Statistical analysis for parameters over time course was performed using a two-way ANOVA with repeated measures for time course effects. Where significant effects were observed post tests were performed using Dunnett’s multiple comparison test. For analysis of endpoint parameters one-way ANOVA with Dunnett’s multiple comparison test was used. Data are presented by individual value with mean as scatter plots. Significant differences between treatment groups compared to Hbb^{th3/4} vehicle group are indicated: * p < 0.05, ** p < 0.01, *** p < 0.001.

Statistical analyses and EC_{50}/IC_{50} value calculations were carried out with Prism software (GraphPad Prism version 7.04, San Diego California USA).

Study approval
The animal studies described in this paper comply with all applicable sections of the law and associated guidelines and were approved by the Veterinary Department of Zurich.
Author contributions

VM wrote the manuscript with input from NN, HS and FD. VM and FD provided guidance in designing of hypothesis and experiments; NN and HS planned and analyzed experiments; AF, AP, AV and CD performed and analyzed experiments; FD was responsible for the project conception.

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References


Figure 1. Identification of ferroportin inhibitors. A. Screening and profiling cascade used to identify ferroportin inhibitors. B. Chemical structure of the ferroportin inhibitor VIT-2763.
Figure 2. VIT-2763 competes with hepcidin for ferroportin binding. A. VIT-2763 prevented the internalization of TMR-hepcidin in J774 cells. Representative fluorescence microscopy pictures from more than 10 independent experiments are shown with J774 cells at high (2 μM) and low concentrations (0.0001 μM) of VIT-2763 or hepcidin before adding TMR-hepcidin (red), nuclei are shown in blue, scale bar corresponds to 25 μm. B. Dose-response curves of VIT-2763 and unlabeled hepcidin in J774 TMR-hepcidin internalization assay, n=3 per concentration. C. Dose-response curves of VIT-2763 and unlabeled hepcidin in fluorescence polarization assay, n=3 per concentration. D. Dose-response curves in iron efflux assay in T47D cells. Shown are dose-response curves of VIT-2763 or hepcidin alone and both in a combination with equimolar concentrations, n=3 or 4 per concentration; E. and F. Dose-response curves of VIT-2763 (E) and hepcidin (F) in HEK-FPN1-GFP ferritin-BLA reporter assay with or without doxycycline induction of ferroportin, n=4 per concentration. B-F, data are presented as mean and SD for each concentration.
Figure 3. VIT-2763 and hepcidin induce ferroportin internalization and ubiquitination.

**A.** Representative images from fluorescence microscopy kinetic analysis of ferroportin internalization and degradation in MDCK cells constitutively expressing human ferroportin with a fluorescent HaloTag (green), nuclei depicted in red. Cells were incubated with either VIT-2763 (20 \( \mu \)M) or hepcidin (1 \( \mu \)M) for the indicated times. Scale bar corresponds to 25 \( \mu \)m. The full kinetic study shown in the figure was performed once. The experiment was repeated at individual time points: once at 6h, 3 times at 20 min and 1h and more than 10 times at 3h and 18h with reproducible results. **B.** Quantification of the ferroportin-associated membrane fluorescence in MDCK cells treated with serial dilutions of either hepcidin or VIT-2763 for 18h, n=3 per concentration, mean±SD for each concentration is shown. **C.** Kinetics of internalization of ferroportin, as depicted by decrease of the membrane-associated ferroportin fluorescence in MDCK cells treated with either hepcidin (1\( \mu \)M) or VIT-2763 (20 \( \mu \)M), n=2 (1-6h), n=3 (18h), mean for each time point is shown. Data in (B) and (C) are presented as mean of the percentage of ferroportin membrane fluorescence relative to untreated cells. **D.** Immunoprecipitation of J774 lysates for ubiquitination and degradation studies of ferroportin. J774 cells were treated with hepcidin (150 nM) or VIT-2763 (100 nM) for 10, 20, 40, 60 or 120 min before harvesting and immunoprecipitation with MTP1 anti-ferroportin antibody. Immunoprecipitates were blotted and stained with either ubiquitin- (upper blot) or ferroportin- (lower blot) specific antibody (F308). The full kinetic study shown in the figure was performed once. The experiment at time points 10 and 120 min was performed five times with reproducible results.
Figure 4. Rapid absorption of the orally dosed VIT-2763 and decrease in serum iron induced by hepcidin and VIT-2763 in rodents. A. Oral PK/PD of VIT-2763 at a single dose of 30 mg/kg in rats, n=3, data shown as mean±SD. B and C. Serum iron levels in C57BL/6 mice treated with either hepcidin (5 mg/kg), n=5 (B) or VIT-2763 (60 mg/kg), n=10 (C) for 1, 3h, 6h and 16h. Data are shown as individual values and mean±SD. In B and C, statistical analysis was performed by comparing all treatment groups to the Hbb<sup>th3/+</sup> vehicle group using one-way ANOVA with Dunnett’s multiple comparison test.
Figure 5. VIT-2763 decreased serum iron and prevented liver iron loading in Hbb\textsuperscript{th3/+} mice. A. VIT-2763 significantly decreased serum iron levels in Hbb\textsuperscript{th3/+} mice three hours after oral dosing at study day 36. B. Total liver iron concentration remained unchanged following 36 days treatment with VIT-2763. C. VIT-2763 prevented liver 59Fe loading in Hbb\textsuperscript{th3/+} mice. D. VIT-2763 reduced the relative spleen weight of Hbb\textsuperscript{th3/+} mice. E. Effect of VIT-2763 on total spleen iron content. A-E, x-axis labels: 1 – vehicle; 2 – VIT-2763 (30 mg/kg); 3 – VIT-2763 (100 mg/kg). A-E, individual values and mean±SD are shown, statistical analysis was performed by comparing all treatment groups to the Hbb\textsuperscript{th3/+} vehicle group using one-way ANOVA with Dunnett’s multiple comparison test, n=10-12. F. Representative pictures from HE (left) and DAB-enhanced Perls staining (right) in spleen sections from vehicle- (top) or VIT-2763-treated (100 mg/kg, middle) Hbb\textsuperscript{th3/+} mice and vehicle-treated WT mice (bottom). Shown are representative pictures from 10 to 12 mice per group and 3 sections from each spleen.
Figure 6. VIT-2763 significantly corrected anemia and improved RBC parameters in Hbb$^{th3/+}$ mice. A. VIT-2763 significantly increased Hb concentration starting at day eight of dosing in Hbb$^{th3/+}$ mice. Mean±SD values of Hb concentrations are shown. Statistical analysis was performed using repeated measures two-way ANOVA with Dunnett’s multiple comparison test to compare all treatment groups to the Hbb$^{th3/+}$ vehicle group over time, n=10-12 mice. At the study end, VIT-2763 increased RBC counts (B), MCHC (C) and decreased reticulocyte counts (D), MCH (E), MCV (F), and RDW (G) in Hbb$^{th3/+}$ mice. B-F, individual values and mean±SD are shown, statistical analysis was performed by comparing all treatment groups to the Hbb$^{th3/+}$ vehicle group using one-way ANOVA with Dunnett’s multiple comparison test, n=10-12 mice.
Figure 7. VIT-2763 treatment improved the ineffective erythropoiesis in BM and spleen of Hbb<sup>th3/+</sup> mice. Gating strategy used to identify erythroid progenitors in BM (A) or spleen (D) by flow cytometry. Representative dot plots from 1 out of 4 independent experiments showing vehicle- or VIT-2763- treated Hbb<sup>th3/+</sup> and WT mice. VIT-2763 decreased the frequency of polychromatic erythroblasts (population in gate 3) in BM (B) and spleen (E). VIT-2763 treatment reduced the percentage of BM (C) and spleen (F) ROS-positive mature erythrocytes. B and E: black symbols show polychromatic erythroblasts and grey symbols show mature erythrocytes. B, C, E and F, x-axis lalbels: 1 – vehicle; 2 – VIT-2763 (30 mg/kg); 3 – VIT-2763 (100 mg/kg). Individual values and mean±SD are shown, statistical analysis was performed by comparing all treatment groups to the Hbb<sup>th3/+</sup> vehicle group using one-way ANOVA with Dunnett’s multiple comparison test, n=10-12 mice.
Figure 8. VIT-2763 reduced the formation of insoluble $\alpha$-gobin aggregates in RBCs of Hbb$^{th3/+}$ mice.  

A. TAU gel electrophoresis of membrane-bound globins in RBCs from Hbb$^{th3/+}$ and WT mice, n=4 to 6, each band is a pool of samples from two mice. Soluble $\alpha$ and $\beta$ hemoglobin from WT RBCs are shown as a reference. Quantification of the signal intensity of the TAU gel $\alpha$-globin bands by densitometry is shown next to the TAU gel picture. Similar effect of VIT-2763 on $\alpha$-globin was documented in 4 independent experiments.  

B. VIT-2763 (60 mg/kg bid for 28 days) reduced the proportion of ROS$^+$ Ter119$^+$ RBCs of Hbb$^{th3/+}$ mice. Individual values and mean±SD are shown, statistical analysis was performed by comparing all treatment groups to the Hbb$^{th3/+}$ vehicle group using one-way ANOVA with Dunnett’s multiple comparison test, n=9-11.
Figure 9. VIT-2763 improved the elimination of mitochondria in RBCs of Hbb^{th3/+} mice.

A and B. Mitochondria are retained in mature RBCs of Hbb^{th3/+} mice and cleared in mature RBCs of Hbb^{th3/+} mice treated with VIT-2763. A. Flow cytometry analysis showing representative dot plots from 1 out of 3 independent experiments. RBCs were gated as mature RBCs (Ter119^{hi}CD71^{neg}), RBC precursors (Ter119^{hi}CD71^{int}), reticulocytes (Ter119^{hi}CD71^{hi}) and analyzed for mitochondrial labeling by MitoTracker Deep Red staining and ROS by CM-H2DCFDA staining. B. Quantification of the percentage of RBCs with mitochondria. Individual values and mean±SD are shown, statistical analysis was performed by comparing all treatment groups to the Hbb^{th3/+} vehicle group using one-way ANOVA with Dunnett’s multiple comparison test, n=10 mice.
Figure 10. VIT-2763 decreased apoptosis and extended the lifespan of RBCs in Hbb\textsuperscript{th3/+} mice.

A. VIT-2763 lowered PS exposure on peripheral RBCs, as detected by decrease in intensity of annexin V staining, n=9-10. B. VIT-2763 reduced the expression of liver Hmox1, as detected by qPCR, n=10-12. A and B, individual values and mean±SD are shown, statistical analysis was performed by comparing all treatment groups to the Hbb\textsuperscript{th3/+} vehicle group using one-way ANOVA with Dunnett's multiple comparison test. C. VIT-2763 (60 mg/kg for 7 weeks) extended the lifespan of RBCs in Hbb\textsuperscript{th3/+} mice. Biotin labeling was performed after 21 days of dosing with VIT-2763. Shown is the percentage of biotinylated Ter119\textsuperscript{+} cells normalized to the percentage of labeled cells at day 1 after biotin injection, n=4-10. Mean±SD values are shown and statistical analysis was performed using repeated measures two-way ANOVA with Dunnett's multiple comparison test to compare all treatment groups to the Hbb\textsuperscript{th3/+} vehicle group over time.
Figure 11. VIT-2763 reduced hypoxia response in RBCs, excessive serum EPO and Erfe expression in spleens of Hbb\textsuperscript{th3/+} mice without effect on liver Hamp. A. Percentage of hypoxic RBCs (left, dot plots) and MFI of the hypoxia probe (right, Hypoxia probe\textsuperscript{*} RBCs) in peripheral blood of Hbb\textsuperscript{th3/+} mice or WT mice, as detected by flow cytometry analysis, n=10-13 mice per group. Representative dot plots showing 1 out of 2 independent experiments. B. Serum EPO was measured by ELISA, n=10-13. C. Spleen Erfe (Fam132), n=4-13 mice per group and liver Hamp (D) gene expression were measured by qPCR, n=10-11 mice. A-D, individual values and mean±SD are shown, statistical analysis was performed by comparing all treatment groups to the Hbb\textsuperscript{th3/+} vehicle group using one-way ANOVA with Dunnett’s multiple comparison test.
Figure 12. Effects of VIT-2763 on myeloid precursors in spleens of Hbb<sup>th3/+</sup> mice.

A. Gating strategy used to identify myeloid cell populations from the spleen of WT and Hbb<sup>th3/+</sup> mice: i) mature neutrophils (Ly6<sup>G</sup><sup>hi</sup>Ly6C<sup>int</sup>), ii) immature myeloid cells (Ly6G<sup>int</sup>Ly6C<sup>int</sup>), iii) resident monocytes (Ly6G<sup>neg</sup>Ly6C<sup>int</sup>), and iv) inflammatory monocytes (Ly6G<sup>neg</sup>Ly6C<sup>hi</sup>). Representative dot plots from 1 out of 3 independent experiments are shown. B. Quantification of percentages of mature neutrophils, immature myeloid cells, resident monocytes and inflammatory monocytes in CD11b<sup>+</sup> spleen cells. Individual values and mean±SD are shown, n=8-13 mice per group. Statistical analysis was performed by comparing all treatment groups to the Hbb<sup>th3/+</sup> vehicle group using one-way ANOVA with Dunnett’s multiple comparison test.