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*Pharmacologic inhibition of hypoxia inducible factor (HIF)-hydroxylases
ameliorates allergic contact dermatitis*

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ABSTRACT

Background: When an immune cell migrates from the bloodstream to a site of chronic inflammation, it experiences a profound decrease in microenvironmental oxygen levels leading to a state of cellular hypoxia. The hypoxia-inducible factor-1 α (HIF-1 α) promotes an adaptive transcriptional response to hypoxia and as such is a major regulator of immune cell survival and function. HIF hydroxylases are the family of oxygen-sensing enzymes primarily responsible for conferring oxygen-dependence upon the HIF pathway. Methods: Using a mouse model of allergic contact dermatitis (ACD), we tested the effects of treatment with the pharmacologic hydroxylase inhibitor DMOG, which mimics hypoxia, on disease development. Results: Re-exposure of sensitized mice to 2,4-dinitrofluorobenzene (DNFB) elicited inflammation, edema, chemokine synthesis (including CXCL1 and CCL5) and the recruitment of neutrophils and eosinophils. Intraperitoneal or topical application of the pharmacologic hydroxylase inhibitors

dymethyloxalylglycine (DMOG) or JNJ1935 attenuated this inflammatory response. Reduced inflammation was associated with diminished recruitment of neutrophils and eosinophils but not lymphocytes. Finally, hydroxylase inhibition reduced cytokine-induced chemokine production in cultured primary keratinocytes through attenuation of the JNK pathway. Conclusion: These data demonstrate that hydroxylase inhibition attenuates the recruitment of neutrophils to the inflamed skin through reduction of chemokine production and increased neutrophilic apoptosis. Thus, pharmacologic inhibition of HIF hydroxylases may be an effective new therapeutic approach in allergic skin inflammation.

INTRODUCTION

Hypoxia is a common microenvironmental feature of inflamed tissues due to increased oxygen consumption, decreased blood flow or a combination of both [1, 2]. Hypoxia activates an adaptive cellular transcriptional response driven by the hypoxia inducible factor (HIF) [3-6]. HIF is a heterodimeric transcription factor formed by the association of oxygen-sensitive HIF- α subunits and a constitutively expressed HIF-1 β subunit. HIF- α subunits are synthesized at a high level in all cells but in the presence of oxygen are hydroxylated by three HIF-prolyl hydroxylases (PHD1-3) on proline residues marking them for ubiquitination by the von Hippel-Lindau E3 ligase complex and proteosomal degradation [5-7]. A further hydroxylation of an asparagine residue within the HIF- α transactivation domain blocks its interaction with the CBP/p300 transcriptional co-activator [4, 8]. As well as conferring oxygen-dependence on HIF, HIF hydroxylases have been implicated in the regulation of other inflammatory and fibrotic pathways including nuclear factor- κ B (NF- κ B) and extracellular signal-regulated kinase (ERK) [10, 12-16]. Pharmacologic HIF-hydroxylase inhibition has been reported to have beneficial effects in various *in vivo* models of inflammatory disease including colitis and chronic kidney disease [9-11]. Furthermore, this pathway has been implicated in contact hypersensitivity to nickel, in allergy to UVB light as well as in the regulation of T cell

mediated responses [17-21]. Therefore, manipulation of the HIF pathway represents a potential strategy for the development of anti-inflammatory drugs. Little is known about the potential of therapeutic application of hydroxylase inhibitors in T-cell driven inflammatory skin disorders.

Allergic contact dermatitis (ACD) is a T cell-mediated inflammatory reaction to epidermal sensitization that causes an over-activation of the immune response upon repeated exposure to the sensitizing hapten [22, 23]. This allergic reaction involves an initial sensitization phase that leads to an elicitation or inflammatory phase [24][25, 26]. Current therapy for ACD is limited to treatment of the inflammatory episodes with anti-inflammatory agents such as corticosteroids [24, 27]. However, long-term systemic or topical treatment of glucocorticoids can result in severe side effects and recalcitrant cases are difficult to treat.

Because of its efficacy in the treatment of inflammation associated with colitis (which shares several key features with ACD), in this study we investigated whether the protective effects of pharmacologic hydroxylase inhibition extend to allergic skin inflammation. Of note, the protective effects of hydroxylase inhibition in the gut is largely through the enhancement of epithelial barrier function (1,10). We report anti-inflammatory actions of hydroxylase inhibitors in allergic skin inflammation mediated through the regulation of chemokine production. Of note, the two hydroxylase inhibitors used in our study, DMOG and JNJ1935, showed similar effects on granulocyte infiltration. JNJ1935 is a more potent and PHD selective inhibitor than DMOG (42). A number of other hydroxylase inhibitors are currently in advanced clinical trials for the treatment of chronic kidney disease associated anemia and have been shown in pre-clinical studies to be effective in the treatment of inflammatory bowel disease (IBD) (10-16).

Hydroxylase inhibitors are currently under advanced clinical investigation for the treatment of anemia making potential repurposing these compounds for other therapeutic applications such as allergic skin disorders a realistic short to medium term possibility [28, 29].

MATERIALS AND METHODS

Reagents

DNFB was obtained from Sigma-Aldrich and diluted in Acetone:olive oil (4:1) at the indicated concentrations. TNF- α (PeproTech, Rocky Hill, NJ), DMOG (Cayman Chemicals, Ann Arbor, MI) and JNJ1935 (Merck Millipore, Darmstadt, Germany), **SB203580 (p38 inhibitor)**, **BAY-117082 (NF- κ B inhibitor)**, **PD98059 (MEK inhibitor)**, **SP600125 (JNK inhibitor)** were prepared according to the manufacturers protocols. For topical application DMOG was reconstituted in acetone and then mixed with olive oil to a 4:1 concentration. For western blot, anti-PHD1, 2 and 3 (Novus, Saint Charles, MO. Diluted 1:500, 1:500 and 1:1000 respectively), anti-phosphoJNK (Santa Cruz, Dallas, TX. Diluted 1:200), anti-phosphoERK (CST, Danvers, MA. Diluted 1:1000), anti-HIF-1 α (BD, San Jose, CA. Diluted 1:500) and anti- β -Actin (Sigma-Aldrich, Saint Louis, MO. Diluted 1:10000) were prepared in 5% skim milk powder in phosphate buffered saline (PBS). For IFHC, anti-CD3 (abcam, Cambridge, MA. Diluted 1:100), anti-Ly6G antibody (Biolegend, San Diego, CA. Diluted 1:250), Anti-CXCR2 (abcam, Cambridge, MA. Diluted 1:100), anti-Rat Alexa Fluor[®] 488 conjugate and 568 conjugate (CST, Danvers, MA. Diluted 1:1000) were used in 5% goat serum in PBS. Human proteome profiler cytokine/chemokine quantikine array and ELISA kits for human CXCL1, CCL5 and IL-8 and mouse myeloperoxidase (MPO), CXCL1/KC and CCL5 kits were obtained from R&D systems (Minneapolis, MN). Taqman probes for human CXCL1, CCL5 and CXCL8 and mouse CXCL1, CCL5, IFN- γ , Glut1, CD4, CD8, granzyme B (GZMB) and TNF- α were from Applied Biosystems (Thermo Fisher Scientific, Cambridge, MA).

Animal studies

10-12 week old wild type female C57BL/6 mice were obtained from Charles River (Wilmington, MA). All *in vivo* experiments were in compliance with regulations of the Health Products Regulatory Authority of Ireland according to protocols approved by the host animal research ethics committee. Mice were sensitized by applying 100µl of 0.5% DNFB to the shaved abdomen for two consecutive days. 4 days after sensitization, mice were treated with vehicle or 8mg/mouse intra-peritoneal DMOG or 0.8mg/mouse intra-peritoneal JNJ1935 or topical DMOG, as indicated. For topical application, 8mg DMOG was applied to the mouse ear at an 8mg/mouse concentration. 1 hour after treatment, mice were challenged by exposing the ears to 20µl of vehicle or 0.2% or 0.3% DNFB as indicated. Measurements of ear thickness were taken using a thickness gauge immediately after challenge and at times 8 and 24 hours following DNFB challenge. Mice were sacrificed and tissues collected 8 or 24 hours after challenge with 0.3% DNFB as indicated.

Primary human Keratinocytes

Human primary adult keratinocytes were isolated from human donor surplus skin after plastic surgery. Cells from 8 different donors were used. Cells were maintained at 37°C in a humidified environment of 21% O₂ and 5% CO₂ (balance N₂) in keratinocyte KBM-gold medium supplemented with human epithelial growth factor, bovine pituitary extract, transferrin, epinephrine, insulin and hydrocortisone (Lonza). Cells were pre-equilibrated in supplement-free medium for 48 hours. For the characterization of the inflammatory profile, cells were treated with 50ng/ml TNF-α for 24 hours. After treatment, the medium was collected for measurement of secreted cytokines/chemokines. For the analysis of the effects of hydroxylase inhibitors on skin inflammation *in vitro*, cells were treated with 1mM DMOG or 100µM JNJ1935 for 1 hour and then treated with TNF-α. For HIF transcription studies the cells were transfected with the HRE-gussia-

luciferase reporter plasmid that contains the gaussia luciferase gene under the control of a promoter that includes tandem repeats of the HIF responsive elements (HRE) as previously described [30]. Transfection was achieved using lipofectamine 3000® (Roche) following manufacturer's indications.

Neutrophil apoptosis

Cells were stimulated with 1µM all-trans retinoic acid (ATRA) to induce differentiation into neutrophils. Neutrophils were then treated with 1mM DMOG and samples collected at 2, 4, 8 and 24 hours to assess and caspase 3/7 activity was measured”

Histology

For histology, tissue was formalin-fixed and paraffin-embedded. 4µm sections were cut from paraffin embedded tissues using a microtome (Leica). Tissues were stained with hematoxylin and eosin and imaged at 20X using the aperio Scanscope console (Leica). For the analysis of T cells, sections were stained with anti-CD3 using alexa fluor 568 secondary antibody. For the study of neutrophilic infiltration, sections were co-stained for Ly6G and CXCR2 using Alexa Fluor 488 and 568 secondary antibodies respectively. 4', 6-diamidino-2-phenylindol (DAPI) was used for nuclear counterstaining. Images at 20X, 40X or 100X magnifications were obtained using a fluorescent microscope. CD3 or Ly6G positive cells in one or two different fields were quantified at 20X using ImageJ image analysis software (National Institute of Health, Bethesda, MD) in a double-blinded fashion. Images of two 20X fields from each mouse were randomized in a double blinded fashion and CD3 or Ly6G positive cells quantified and expressed as an average of the 2 fields. Giemsa staining was used to identify mast cells. Mast cell quantification was developed in a double blinded fashion. Eosinophils were counted from H&E images in a double blinded fashion.

ELISA, chemokine/cytokine array and Western blot

For protein studies, half mouse ears (10-15mg) were homogenized in radio-immunoprecipitation assay (RIPA) buffer containing protease inhibitor cocktail (Sigma-Aldrich, Saint Louise, MO) using Qiagen stainless steel beads and the tissuelyser II (Qiagen). Samples were centrifuged 2-3 times at 14000rpm at 4°C and protein supernatants collected for ELISA and WB. For in vitro keratinocyte studies, medium supernatants were collected for ELISA and chemokine/cytokine array analysis was performed. For western blot studies, cells were lysed in the same lysis buffer used for mouse ears and centrifuged to obtain protein supernatants. Equal amounts of protein per each sample were used in all cases.

Quantitative real time polymerase chain reaction

For RNA isolation, tissue was stored in RNA later (Qiagen) at 4°C overnight. Samples were homogenized in trizol (Thermo Fisher Scientific, Cambridge, MA). For in vitro cultured keratinocytes, cells were lysed in trizol. RNAs were then extracted using a standard phenolic extraction protocol. Complementary DNA was synthesized and quantitative real time polymerase chain reaction carried out as previously described [31].

Statistical analysis

Graph Pad Prism version 5.0 was used for all statistical analysis. One-way ANOVA followed by a Newman-Keuls post-test was used for comparison of multiple groups. Student's t-test was used for individual group comparisons. Differences were considered statistically significant when the p-value was ≤ 0.05 . There was a minimum of 3 experimental replicates per group.

RESULTS

1. Hydroxylase inhibition reduces inflammation in allergic contact dermatitis.

Histologic analysis of DNFB-sensitized mouse ear cross-sections revealed an increase in ear thickness following secondary DNFB challenge which was attenuated by DMOG treatment (figure 1A & 1B). CXCL1 and CCL5 drive DNFB-induced dermatitis [22, 32, 33]. DMOG treatment attenuated DNFB-induced CXCL1 and CCL5 expression (figure 1C and 1D). We next investigated the effects of a second hydroxylase inhibitor JNJ1935 on DNFB-mediated inflammation. Ears of sensitized mice challenged with DNFB displayed a consistent increase in ear thickness and edema accompanied by increased IFN- γ , CXCL-1 and CCL-5 transcripts (figure 1E-I). JNJ1935 treatment significantly reduced ear thickness, edema and CXCL-1 expression. These data demonstrate that hydroxylase inhibition reduces inflammation in allergic contact dermatitis.

2. DNFB-mediated inflammation induces transcriptional reprogramming of HIF hydroxylase expression.

We next investigated the expression pattern of PHD1-3 in mouse ears. PHD1 was robustly expressed and did not differ in expression levels between vehicle and DNFB-challenged ears (Figure 2A and 2B). PHD2 was expressed in the ears of vehicle treated mice and was downregulated in DNFB challenged ears (figure 2A and 2C). PHD2 is the main regulator of HIF- α stability and its degradation has been proposed as an alternative mechanism of HIF regulation triggered by TGF- β and endothelin [34, 35]. PHD3 expression levels were generally lower and not statistically significantly changed in response to DNFB challenge (figure 2A and 2D). PHD3 has been purposed as a HIF inducible protein implicated in inflammation through regulation of neutrophil survival [36]. Compared to vehicle, DNFB challenged ears demonstrated increased expression of Glut1, a HIF-dependent gene (figure 2E).

3. Hydroxylase inhibition prevents neutrophil recruitment in ACD.

We next analyzed the effects of hydroxylase inhibition on T cell infiltration. Mice challenged with DNFB demonstrated increased CD3 positive lymphocytes in the dermis which was not affected by DMOG treatment (Figure 3A-B). Furthermore, mice challenged with 0.3% DNFB for 24 hours did not have a detectable increase in CD4 levels, but demonstrated elevated CD8 expression implicating a dominance of a CD8⁺ cytotoxic T-lymphocyte infiltrate (figure 3C-3D). In addition, DNFB challenge increased the expression of granzyme B (GZMB), confirming the presence of CD8⁺ T cells (figure 3E). However, treatment with JNJ1935 did not reduce the number of CD8⁺ T-cells or granzyme B levels suggesting that hydroxylase inhibition does not mediate its anti-inflammatory effects via altering T cell responses in this model (Figure 3D-E).

Neutrophils also play a central role in DNFB-induced dermatitis [22, 32]. CXCL1 is the key chemokine involved in the recruitment of neutrophils via activation of the CXCR2 receptor [37-39]. Since CXCL1 protein and RNA expression was reduced by hydroxylase inhibition, we next investigated its impact on DNFB-mediated neutrophil infiltration. Mouse ear cross sections were co-stained for the neutrophil marker Ly6G and the chemokine receptor CXCR2 using double-immunofluorescence. In most cases, Ly6G and CXCR2 were co-expressed in infiltrating neutrophils suggesting the presence of CXCL1 sensitive neutrophils (Supplementary Figure 1). Comparison between vehicle and DNFB challenged ear cross-sections showed a profound increase in neutrophil presence (figure 3F). These neutrophils were concentrated in the dermis, showing the correlation between the dermal inflammatory reaction and neutrophil infiltration. Mice treated with intra-peritoneal JNJ1935 demonstrated a lower number of infiltrating neutrophils in the dermis (figure 3F). Quantification of Ly6G positive cells showed higher number of neutrophils in DNFB challenged ears compared to vehicle controls (figure 3G). These Ly6G positive cells were significantly reduced in mice treated with JNJ1935 (figure 3G). To further analyze the effect of

hydroxylase inhibition in neutrophil infiltration we measured the amount of myeloperoxidase (MPO) in mouse ear protein homogenates. DNFB dramatically increased MPO levels compared to vehicle reflecting increased numbers of neutrophils (figure 3H). In contrast, mice treated with JNJ1935 had significantly lower MPO values confirming its inhibitory effect on neutrophil-mediated DNFB-induced inflammation (figure 3H). In addition to the effects detected on neutrophils, we also analyzed the effect of hydroxylase inhibitors on eosinophils. We found that eosinophils were significantly increased in the ears of DNFB sensitized and challenged mice (supplementary figure 2A-C). This DNFB-induced increase in eosinophil numbers increase was inhibited in DMOG or JNJ1935 mice (supplementary figure 2A-C).

In order to extend our analysis of inflammatory infiltrates, we also investigated whether hydroxylase inhibitors affect mast cell infiltration. Mast cells were increased in the dermis of mice challenged with DNFB after sensitization but were not reduced by hydroxylase inhibition (supplementary figure 2). Thus, our data indicate that hydroxylase inhibitors selectively affect eosinophil and neutrophil but not lymphocyte or mast cell infiltration in murine ACD.

Together, these results demonstrate that the anti-inflammatory effect of hydroxylase inhibitors in DNFB-induced dermatitis is associated with reduced eosinophil and neutrophil (but not T-cell) infiltration into the inflamed tissue.

4. Hydroxylase inhibition reduces chemokine production in human primary keratinocytes

Keratinocytes play an important role in skin inflammatory diseases through secretion of chemokines and cytokines which recruit neutrophils and activate downstream inflammatory pathways [40]. In ACD, keratinocytes both respond to and express TNF- α [24]. In our experiments, sensitized mice challenged with DNFB expressed increased levels of TNF- α mRNA which were not affected by hydroxylase inhibition (figure 4A). In vitro stimulation of primary human keratinocytes with TNF- α led to the production of a range of cytokines and chemokines including CXCL1, IL8 and CCL5 (Supplementary figure 3) [41]. Treatment of primary human keratinocytes with either DMOG or JNJ1935 induced HIF stabilization and HIF-dependent transcriptional responses demonstrating responsiveness of this cell type to hydroxylase inhibition (figure 4B). Treatment with JNJ1935 reduced TNF- α -induced secretion of CCL5 and CXCL1, but not IL-8 (figure 4C-4E). Moreover, TNF- α increased the expression of CCL5 (up to 4 fold), CXCL1 (up to 4 fold) and CXCL8 (IL-8) (up to 10 fold) mRNA transcripts compared with vehicle treated cells. JNJ1935 caused a significant reduction of CCL5 and CXCL1 RNA but did not affect the expression of IL-8 (figure 4F-4H). Similarly, stimulation with IL-1 β induced production of CCL5, CXCL1 and IL-8 from keratinocytes and treatment with JNJ1935 reduced IL-1 β -induced CCL5 and CXCL1 but did not affect IL-8 (data not shown). These results show an inhibitory effect of hydroxylase inhibitors on the expression of CXCL1 and CCL5 from primary human keratinocytes.

5. TNF- α mediated JNK phosphorylation is reduced by hydroxylase inhibition

The production of inflammatory chemokines in response to DNFB is controlled by the NF- κ B and MAPK pathways [24, 43]. We next investigated whether the anti-inflammatory effects of hydroxylase inhibition were due to the blockade of MAPK/NF- κ B pathways. Using TNF-induced CCL5 expression as a readout, we compared the effects of JNJ1935 to that of inhibitors of the NF-

κB, ERK, JNK and p38 pathways. As previously shown JNJ1935 reduced CCL5 secretion (Figure 5A). Only the JNK inhibitor SP600125 caused a significant reduction of TNF-α mediated CCL5 production (Figure 5A). Furthermore, TNF-α transiently increased JNK phosphorylation peaking at 0.5 and 2 hours after stimulation in a manner that was attenuated by JNJ1935 treatment (Figure 5B and 5C).

Another possible mechanism whereby hydroxylase inhibition could reduce neutrophil infiltration is by triggering apoptotic cell death. In order to investigate this, we used HL60 cells. As seen in figure 5D, we found DMOG to induce activation of caspase3/7 in a time dependent manner. This pro-apoptotic action was comparable to that induced by the positive control etoposide. Therefore, in addition to reducing JNK mediated chemokine production, hydroxylase inhibitors also increase neutrophil apoptosis (figure 5E). From these data, we hypothesize that the anti-inflammatory effects of hydroxylase inhibition is mediated at least in part through attenuation of the JNK pathway in this model and the induction of neutrophil apoptosis.

6. Topical administration of DMOG prevents DNFB mediated neutrophil infiltration

Intraperitoneal administration of hydroxylase inhibitors may cause erythropoiesis. We next investigated whether topical application of the hydroxylase inhibitor DMOG has anti-inflammatory actions in DNFB treated mice. Haematoxylin and eosin (H&E) staining of mouse ears revealed severe DNFB-induced dermal edema and neutrophil infiltration following challenge (figure 6A-6D). Mice treated with topical DMOG displayed significantly diminished ear thickness and neutrophil infiltration (figure 6A-6D). These results show that topical application of hydroxylase inhibitors have anti-inflammatory properties.

DISCUSSION

In this study, we investigated the impact of hydroxylase inhibitors on allergic skin inflammation (Type-IV hypersensitivity).

Inflammatory skin disorders including AD, psoriasis or ACD are common dermatological diseases and thus improved therapies with high efficacy and a low side effect profile are still an unmet clinical need [24, 44]. ACD is caused by a severe inflammatory response upon contact with a hapten to which an individual has become sensitized. Hapten challenge triggers a multistep inflammatory response in which T cells and neutrophils are key effectors [22, 25]. This response is orchestrated by the release of cytokines and chemokines leading to further inflammation and tissue edema. The DNFB model of ACD is a common model for the study of allergic skin inflammation [24, 25]. Challenge of mouse ears of DNFB-sensitized mice induced a severe inflammatory reaction with formation of edema in the dermis. Dermal edema was accompanied by an increase in CXCL1 and CCL5 expression. These chemokines are crucial for the recruitment of neutrophils and T lymphocytes, respectively [45-47]. Intraperitoneal treatment with hydroxylase inhibitors reduced ear edema in a manner which was associated with diminished expression and release of CXCL1 and CCL5. In addition, DNFB-induced inflammation differentially regulated the expression of oxygen sensing hydroxylases. Firstly, our studies showed that PHD2 was down regulated in DNFB challenged skin. PHD-2 is the predominant PHD isoform expressed through-out the body and its suppression is sufficient to stabilize HIF- α [48]. The down-regulation of PHD2 has been purposed as a mechanism of regulation of the HIF pathway mediated by different proinflammatory stimuli [34, 35]. In line with this evidence, our studies showed that DNFB is capable of increasing the expression of the HIF target gene Glut1. This further indicates that DNFB-induced inflammation is related to the establishment of a hypoxic response and modulation of the HIF pathway. This supports the concept that the HIF pathway is plays an active role in allergic skin disease.

T cells are key drivers of the allergic response that governs DNFB-mediated inflammation [22, 50, 51]. In our studies, the expression of CD4 was not detected 24 hours after challenge in mouse ears. In contrast, CD8 and GZMB were significantly upregulated at the challenged site suggesting a predominance of CD8⁺ T cells. Hydroxylase inhibitors did not affect the expression of T cell markers investigated, suggesting that the anti-inflammatory properties of the drugs are not through reducing lymphocyte recruitment. Multiple studies have described the role of CXCL1-mediated neutrophil recruitment in the initiation stages of DNFB-induced ACD [32, 47, 52]. Importantly, the presence of neutrophils is central to the establishment of the T cell-mediated response that regulates contact hypersensitivity, highlighting the importance of neutrophils in ACD [22, 53]. Mice sensitized and challenged with DNFB had a large amount of infiltrating Ly6G/CXCR2 positive neutrophils in the dermis. CXCR2 is the main receptor responsible for CXCL1-dependent recruitment of neutrophils [37]. Studies using models of arthritis have highlighted the importance of this axis. In these studies, blockade of CXCR2 as well as knock out of CXCL1 had anti-inflammatory effects through reduced neutrophil recruitment [37, 54]. In the context of skin inflammation, CXCR2^{-/-} mice were protected against DNFB-induced dermatitis through reduced recruitment of polymorphonuclear cells whereas other studies correlate reduced CXCL1 with reduced inflammation [38, 52]. In line with this evidence, hydroxylase inhibitor mediated reduction of CXCL1 expression and secretion was associated to a reduction of neutrophil infiltration, confirming a repression of the CXCL1-induced neutrophil response during acute ACD. Of note, we also found similar effects of hydroxylase inhibitors on eosinophils, indicating that the effects on neutrophils might be extended to other granulocyte populations.

Beyond the formation of physical barriers, the active role of epithelial cells in inflammatory diseases is well documented [7, 52, 55-57]. In the case of the skin, a number of studies show the importance of keratinocytes and endothelial cells in the elicitation of inflammation [52, 58-61].

TNF- α is a strong stimulus for keratinocytes and plays important roles in skin inflammation. In our studies, TNF- α expression was increased in DNFB induced ACD but was not affected by hydroxylase inhibitors. TNF- α stimulation of primary human keratinocytes isolated from multiple donors increased the expression and release of multiple cytokines and chemokines including CXCL1, CCL5 or IL-8 supporting a fundamental role of the keratinocytes in orchestrating skin inflammation. Hydroxylase inhibitors blocked the production and expression of CXCL1 and CCL5 but did not affect that of IL-8. These *in vitro* findings were in line with our *in vivo* observations and support the anti-inflammatory actions of these drugs via reduced recruitment of inflammatory cells such as neutrophils.

Several different pathways including NF- κ B and MAPK pathways have been reported to regulate inflammation in different cell and in vivo models. In our *in vitro* model, TNF mediated CCL-5 production was reduced in cells treated with the JNK inhibitor SP600125 in a manner similar to JNJ1935. Of note, only JNJ1935 showed repressive effects on CXCL1 release compared to specific inhibitors of NF- κ B, ERK, JNK or p38 kinases. Further, JNJ1935 reduced TNF α -induced JNK phosphorylation suggesting a potential effect of hydroxylase inhibition on the JNK pathway. Another key aspect to consider for the translation of these inhibitors into new skin therapies is that of their route of administration. In many cases, the topical route can be exploited for the development of therapies for skin disease. In our studies, topical administration of DMOG achieved similar results to those seen with intraperitoneal administration, reducing ear edema and the recruitment of neutrophils. Thus, our results support a model whereby Hydroxylase inhibition attenuates CXCL1 and CCL5 production and consequently blocks downstream events leading to neutrophil recruitment during skin inflammation. Of note, a similar mechanism was recently proposed in the context of pulmonary infection. Increased susceptibility of myeloid-deficient HIF1 α mice to infection was due to decreased production of CXCL1 and increased neutrophil apoptosis,

resulting in decreased neutrophil infiltration [62]. For instance hydroxylase inhibition might regulate chemokine production causing inhibition of proinflammatory immune responses.

Several authors have implicated oxygen sensing hydroxylases in the regulation of inflammatory cell survival. Of note, Walmsley and colleagues described a key role of PHD3 in the induction of neutrophil survival *in vitro* and *in vivo* (36). Given the increased expression of PHD3 in DNFB challenged skin found in our studies, we investigated whether hydroxylase inhibitors induced neutrophil apoptosis. In line with a role for hydroxylases in the regulation of neutrophil survival, hydroxylase inhibition with DMOG induced time-dependent cell death in cultured neutrophils. Current therapies for ACD are based on the use of anti-inflammatory drugs such as topical/systemic glucocorticosteroids, or immunomodulating ultraviolet light therapy [63-65]. However, all therapies are still limited for different reasons, whether as to efficacy in severe cases or due to various side effect profiles (e.g. skin atrophy, infections, skin dryness or increased cancer risk after long-term repeated phototherapy). In addition, bexarotene can induce an irritant CD and glucocorticosteroids rarely an allergic contact dermatitis as well [65], and systemic approaches induce harmful, partly irreversible adverse events under long-term therapy (66). Here, we have shown for the first time that hydroxylase inhibitors may exert a beneficial effect for the treatment of allergic contact dermatitis and probably other chronic inflammatory skin diseases in which neutrophils and eosinophils are involved..

REFERENCES

1. Colgan, S.P. and C.T. Taylor, *Hypoxia: an alarm signal during intestinal inflammation*. Nature Reviews Gastroenterology & Hepatology, 2010. **7**(5): p. 281-287.
2. Karhausen, J., et al., *Epithelial hypoxia-inducible factor-1 is protective in murine experimental colitis*. Journal of Clinical Investigation, 2004. **114**(8): p. 1098-1106.
3. Wang, G.L., et al., *Hypoxia-Inducible Factor-1 Is a Basic-Helix-Loop-Helix-Pas Heterodimer Regulated by Cellular O-2 Tension*. Proceedings of the National Academy of Sciences of the United States of America, 1995. **92**(12): p. 5510-5514.
4. Mahon, P.C., K. Hirota, and G.L. Semenza, *FIH-1: a novel protein that interacts with HIF-1 alpha and VHL to mediate repression of HIF-1 transcriptional activity*. Genes & Development, 2001. **15**(20): p. 2675-2686.
5. Maxwell, P.H., et al., *The tumour suppressor protein VHL targets hypoxia-inducible factors for oxygen-dependent proteolysis*. Nature, 1999. **399**(6733): p. 271-275.
6. Hewitson, K.S., C.J. Schofield, and P.J. Ratcliffe, *Hypoxia-inducible factor prolyl-hydroxylase: Purification and assays of PHD2*. Oxygen Biology and Hypoxia, 2007. **435**: p. 25-42.
7. Manresa, M.C. and C.T. Taylor, *Hypoxia Inducible Factor (HIF) Hydroxylases as Regulators of Intestinal Epithelial Barrier Function*. Journal of Cellular and Molecular Gastroenterology and Hepatology 2017.
8. Lando, D., et al., *Asparagine hydroxylation of the HIF transactivation domain: A hypoxic switch*. Science, 2002. **295**(5556): p. 858-861.
9. Robinson, A., et al., *Mucosal protection by hypoxia-inducible factor prolyl hydroxylase inhibition*. Gastroenterology, 2008. **134**(1): p. 145-155.
10. Cummins, E.P., et al., *The hydroxylase inhibitor dimethyloxalylglycine is protective in a murine model of colitis*. Gastroenterology, 2008. **134**(1): p. 156-165.
11. Hindryckx, P., et al., *Hydroxylase Inhibition Abrogates TNF-alpha-Induced Intestinal Epithelial Damage by Hypoxia-Inducible Factor-1-Dependent Repression of FADD*. Journal of Immunology, 2010. **185**(10): p. 6306-6316.
12. Cummins, E.P., et al., *Prolyl hydroxylase-1 negatively regulates I kappa B kinase-beta, giving insight into hypoxia-induced NF kappa B activity*. Proceedings of the National Academy of Sciences of the United States of America, 2006. **103**(48): p. 18154-18159.
13. Tambuwala, M.M., et al., *Loss of Prolyl Hydroxylase-1 Protects Against Colitis Through Reduced Epithelial Cell Apoptosis and Increased Barrier Function*. Gastroenterology, 2010. **139**(6): p. 2093-2101.
14. Scholz, C.C., et al., *Regulation of IL-1 beta-induced NF-kappa B by hydroxylases links key hypoxic and inflammatory signaling pathways*. Proceedings of the National Academy of Sciences of the United States of America, 2013. **110**(46): p. 18490-18495.
15. Van Welden, S., et al., *Differential expression of prolyl hydroxylase 1 in patients with ulcerative colitis versus patients with Crohn's disease/infectious colitis and healthy controls*. Journal of Inflammation-London, 2013. **10**.
16. Manresa MC, T.M., Radhakrishnan P, Harnoss JM, Brown E, Cavadas MA, Keogh CE, Cheong A, Barrett KE, Cummins EP, Schneider M, Taylor CT., *Hydroxylases regulate intestinal fibrosis through the suppression of ERK mediated TGF-β1 signaling*. American Journal of Physiology-Gastrointestinal and Liver Physiology, 2016.
17. Viemann, D., et al., *The contact allergen nickel triggers a unique inflammatory and proangiogenic gene expression pattern via activation of NF-kappa B and hypoxia-inducible factor-1 alpha*. Journal of Immunology, 2007. **178**(5): p. 3198-3207.
18. Rezvani, H.R., et al., *Hypoxia-inducible factor-1 alpha, a key factor in the keratinocyte response to UVB exposure*. Journal of Biological Chemistry, 2007. **282**(22): p. 16413-16422.
19. Cho, J.L., M. Allanson, and V.E. Reeve, *Hypoxia inducible factor-1 alpha contributes to UV radiation-induced inflammation, epidermal hyperplasia and immunosuppression in mice*. Photochemical & Photobiological Sciences, 2012. **11**(2): p. 309-317.

20. Lee, J.H., et al., *E3 Ubiquitin Ligase VHL Regulates Hypoxia-Inducible Factor-1 alpha to Maintain Regulatory T Cell Stability and Suppressive Capacity*. *Immunity*, 2015. **42**(6): p. 1062-1074.
21. Clambey, E.T., et al., *Hypoxia-inducible factor-1 alpha-dependent induction of FoxP3 drives regulatory T-cell abundance and function during inflammatory hypoxia of the mucosa*. *Proceedings of the National Academy of Sciences of the United States of America*, 2012. **109**(41): p. E2784-E2793.
22. Kish, D., et al., *Hapten application to the skin induces an inflammatory program directing hapten-primed effector CD8 T cell interaction with hapten-presenting endothelial cells*. *Journal of Immunology*, 2011. **186**.
23. Spiewak, R., *Immunotherapy of allergic contact dermatitis*. *Immunotherapy*, 2011. **3**(8): p. 979-996.
24. Kaplan, D.H., B.Z. Igyarto, and A.A. Gaspari, *Early immune events in the induction of allergic contact dermatitis*. *Nature Reviews Immunology*, 2012. **12**(2): p. 114-124.
25. Vocanson, M., et al., *Effector and regulatory mechanisms in allergic contact dermatitis*. *Allergy*, 2009. **64**(12): p. 1699-1714.
26. Bangsgaard, N., et al., *Lack of effect of ustekinumab in treatment of allergic contact dermatitis*. *Contact Dermatitis*, 2011. **65**(4): p. 227-230.
27. Martin, S.F., et al., *Mechanisms of chemical-induced innate immunity in allergic contact dermatitis*. *Allergy*, 2011. **66**(9): p. 1152-1163.
28. Besarab, A., et al., *Roxadustat (FG-4592): Correction of Anemia in Incident Dialysis Patients*. *Journal of the American Society of Nephrology*, 2016. **27**(4): p. 1225-1233.
29. Provenzano, R., et al., *Oral Hypoxia-Inducible Factor Prolyl Hydroxylase Inhibitor Roxadustat (FG-4592) for the Treatment of Anemia in Patients with CKD*. *Clinical Journal of the American Society of Nephrology*, 2016. **11**(6): p. 982-991.
30. Nguyen, L.K., et al., *A dynamic model of the hypoxia-inducible factor 1 alpha (HIF-1 alpha) network*. *Journal of Cell Science*, 2013. **126**(6): p. 1454-1463.
31. Fitzpatrick, S.F., et al., *An Intact Canonical NF-kappa B Pathway Is Required for Inflammatory Gene Expression in Response to Hypoxia*. *Journal of Immunology*, 2011. **186**(2): p. 1091-1096.
32. Kish, D.D., et al., *Neutrophil Expression of Fas Ligand and Perforin Directs Effector CD8 T Cell Infiltration into Antigen-Challenged Skin*. *Journal of Immunology*, 2012. **189**(5): p. 2191-2202.
33. Canavese, M., F. Altruda, and L. Silengo, *Therapeutic Efficacy and Immunological Response of CCL5 Antagonists in Models of Contact Skin Reaction*. *Plos One*, 2010. **5**(1).
34. McMahon, S., et al., *Transforming growth factor beta 1 induces hypoxia-inducible factor-1 stabilization through selective inhibition of PHD2 expression*. *Journal of Biological Chemistry*, 2006. **281**(34): p. 24171-24181.
35. Spinella, F., et al., *Endothelin-1 Inhibits Prolyl Hydroxylase Domain 2 to Activate Hypoxia-Inducible Factor-1 alpha in Melanoma Cells*. *Plos One*, 2010. **5**(6).
36. Walmsley, S.R., et al., *Prolyl hydroxylase 3 (PHD3) is essential for hypoxic regulation of neutrophilic inflammation in humans and mice*. *Journal of Clinical Investigation*, 2011. **121**(3): p. 1053-1063.
37. Ritzman, A.M., et al., *The Chemokine Receptor CXCR2 Ligand KC (CXCL1) Mediates Neutrophil Recruitment and Is Critical for Development of Experimental Lyme Arthritis and Carditis*. *Infection and Immunity*, 2010. **78**(11): p. 4593-4600.
38. Cattani, F., et al., *The role of CXCR2 activity in the contact hypersensitivity response in mice*. *European Cytokine Network*, 2006. **17**(1): p. 42-48.
39. Eash, K.J., et al., *CXCR2 and CXCR4 antagonistically regulate neutrophil trafficking from murine bone marrow*. *Journal of Clinical Investigation*, 2010. **120**(7): p. 2423-2431.
40. Banno, T., A. Gazel, and M. Blumenberg, *Effects of tumor necrosis factor-alpha (TNF alpha) in epidermal keratinocytes revealed using global transcriptional profiling*. *Journal of Biological Chemistry*, 2004. **279**(31): p. 32633-32642.
41. Wakabayashi, T., et al., *IFN-gamma and TNF-alpha are involved in urushiol-induced contact hypersensitivity in mice*. *Immunology and Cell Biology*, 2005. **83**(1): p. 18-24.

42. Barrett, T.D., et al., *Pharmacological Characterization of 1-(5-Chloro-6-(trifluoromethoxy)-1H-benzimidazol-2-yl)-1H-pyrazole-4-carboxylic Acid (JNJ-42041935), a Potent and Selective Hypoxia-Inducible Factor Prolyl Hydroxylase Inhibitor*. Molecular Pharmacology, 2011. **79**(6): p. 910-920.
43. Ayush, O., et al., *Glutamine Suppresses DNFB-Induced Contact Dermatitis by Deactivating p38 Mitogen-Activated Protein Kinase via Induction of MAPK Phosphatase-1*. Journal of Investigative Dermatology, 2013. **133**(3): p. 723-731.
44. Palmer, C.N.A., et al., *Common loss-of-function variants of the epidermal barrier protein filaggrin are a major predisposing factor for atopic dermatitis*. Nature Genetics, 2006. **38**(4): p. 441-446.
45. Hong, M., et al., *Chemotherapy Induces Intratumoral Expression of Chemokines in Cutaneous Melanoma, Favoring T-cell Infiltration and Tumor Control*. Cancer Research, 2011. **71**(22): p. 6997-7009.
46. Luther, S.A. and J.G. Cyster, *Chemokines as regulators of T cell differentiation*. Nature Immunology, 2001. **2**(2): p. 102-107.
47. Engeman, T., et al., *The intensity of neutrophil infiltration controls the number of antigen-primed CD8 T cells recruited into cutaneous antigen challenge sites*. Journal of Leukocyte Biology, 2004. **76**(5): p. 941-949.
48. Berra, E., et al., *HIF prolyl-hydroxylase 2 is the key oxygen sensor setting low steady-state levels of HIF-1 alpha in normoxia*. Embo Journal, 2003. **22**(16): p. 4082-4090.
49. Escribese, M.M., et al., *The Prolyl Hydroxylase PHD3 Identifies Proinflammatory Macrophages and Its Expression Is Regulated by Activin A*. Journal of Immunology, 2012. **189**(4): p. 1946-1954.
50. Vocanson, M., et al., *Contribution of CD4(+) and CD8(+) T-cells in contact hypersensitivity and allergic contact dermatitis*. Expert Rev Clin Immunol, 2005. **1**(1): p. 75-86.
51. Goubier, A., et al., *Invariant NKT cells suppress CD8(+) T-cell-mediated allergic contact dermatitis independently of regulatory CD4(+) T cells*. J Invest Dermatol, 2013. **133**(4): p. 980-7.
52. Honda, T., et al., *Prostaglandin E-2-EP3 signaling suppresses skin inflammation in murine contact hypersensitivity*. Journal of Allergy and Clinical Immunology, 2009. **124**(4): p. 809-818.
53. Dilulio, N.A., et al., *Gro alpha-mediated recruitment of neutrophils is required for elicitation of contact hypersensitivity*. European Journal of Immunology, 1999. **29**(11): p. 3485-3495.
54. Barsante, M.M., et al., *Blockade of the chemokine receptor CXCR2 ameliorates adjuvant-induced arthritis in rats*. British Journal of Pharmacology, 2008. **153**(5): p. 992-1002.
55. Fournier, B.M. and C.A. Parkos, *The role of neutrophils during intestinal inflammation*. Mucosal Immunology, 2012. **5**(4): p. 354-366.
56. Swamy, M., et al., *Epithelial decision makers: in search of the 'epimmunome'*. Nature Immunology, 2010. **11**(8): p. 656-665.
57. Steinhoff, M., et al., *Modern aspects of cutaneous neurogenic inflammation*. JAMA Dermatology, 2003.
58. Purwar, R., T. Werfel, and M. Wittmann, *IL-13-stimulated human keratinocytes preferentially attract CD4(+)CCR4(+) T cells: Possible role in atopic dermatitis*. Journal of Investigative Dermatology, 2006. **126**(5): p. 1043-1051.
59. Mori, T., et al., *Cutaneous hypersensitivities to hapten are controlled by IFN-gamma-upregulated keratinocyte Th1 chemokines and IFN-gamma-downregulated Langerhans cell Th2 chemokines*. Journal of Investigative Dermatology, 2008. **128**(7): p. 1719-1727.
60. Honda, T., et al., *Update of Immune Events in the Murine Contact Hypersensitivity Model: Toward the Understanding of Allergic Contact Dermatitis*. Journal of Investigative Dermatology, 2013. **133**(2): p. 303-315.
61. Seeliger, S., et al., *Proinflammatory role of proteinase-activated receptor-2 in humans and mice during cutaneous inflammation in vivo*. FASEB Journal, 2003.
62. Shepardson, K.M., et al., *Myeloid Derived Hypoxia Inducible Factor 1-alpha Is Required for Protection against Pulmonary Aspergillus fumigatus Infection*. Plos Pathogens, 2014. **10**(9).
63. Cohen, H., *Treatment of irritant and allergic contact dermatitis*. Dermatologic Therapy, 2004. **17**(4): p. 334-340.

64. Anveden, I., et al., *Oral prednisone suppresses allergic but not irritant patch test reactions in individuals hypersensitive to nickel*. *Contact Dermatitis*, 2004. **50**(5): p. 298-303.
65. Gonul, M. and U. Gul, *Detection of contact hypersensitivity to corticosteroids in allergic contact dermatitis patients who do not respond to topical corticosteroids*. *Contact Dermatitis*, 2005. **53**(2): p. 67-70.

FIGURE LEGENDS

Figure 1. *Hydroxylase inhibitors reduce inflammation in DNFB-induced acute dermatitis.* (A) haematoxylin and eosin staining of mouse ear cross-sections from mice treated or not with intraperitoneal injections of 8mg/mouse DMOG and challenged with vehicle or DNFB (n=6). (B) quantification of the increment in ear thickness in mice treated as described in A. (C-D) ELISA of mouse CXCL1 and CCL5 from ear homogenates of mice treated as described in A (n=4). (E) quantification of the increment in ear thickness in mice treated or not with intraperitoneal injections of 0.8mg/mouse JNJ1935 and challenged with DNFB (n=5). (F) haematoxylin and eosin staining of mouse ear cross-sections from mice treated as described in E. (G-I) qRT-PCR of IFN- γ , CXCL1 and CCL5 in mouse ears from mice treated as described in E (n=5). *means $p \leq 0.05$; **means $p \leq 0.01$; ***means $p \leq 0.001$.

Figure 2. *Differential profile of expression of HIF-prolyl hydroxylases in DNFB-induced dermatitis.* (A) Western blot of protein extracts of mouse ears sensitized with DNFB and then challenged with vehicle or DNFB for 8 hours. (B-D) densitometry of PHD1 (B), PHD2 (C) and PHD3 (D) comparing mice treated as described in A (n $\geq$ 4). (E) qRT-PCR of Glut1 in mouse ears challenged with vehicle or DNFB for 24 hours and untreated or treated with 0.8mg/mouse JNJ1935 (n=5). *means $p \leq 0.05$; ***means $p \leq 0.001$.

Figure 3. *Hydroxylase inhibitors reduce DNFB-mediated Ly6G/CXCR2 positive neutrophil infiltration.* (A) Representative images of immunofluorescence of mouse ear cross-sections stained for CD3 of mice treated or not with 8mg/mouse IP DMOG and challenged with DNFB for 24h. (B) Epidermal and dermal quantification of CD3 positive staining in mouse ear cross-sections from mice treated as described in A. (C-E) qRT-PCR of CD4, CD8 and GZMB in mouse ears challenged with vehicle or DNFB for 24 hours and untreated or treated with 0.8mg/mouse JNJ1935 (n=5). (F) Representative images of immunofluorescence of mouse ear cross-sections stained for Ly6G/CXCR2 in mice treated or not with intraperitoneal injections of 0.8mg/mouse JNJ1935 before challenge with topical vehicle or DNFB (20X and 40X) (n=6). (G) quantification of Ly6G positive neutrophils in the dermis of mice treated as in F (n=6). (H) ELISA of mouse MPO from ear homogenates of mice treated as described in E (n=4). *means $p \leq 0.05$; **means $p \leq 0.01$; ***means $p \leq 0.001$.

Figure 4. *Hydroxylase inhibitors reduce TNF- α induced production of chemokines in human primary keratinocytes.* (A) qRT-PCR of TNF- α in ears of mice treated or not with intraperitoneal injections of 0.8mg/mouse JNJ1935 and challenged with vehicle or DNFB (n=5). (B) **above**, representative western blot of HIF-1 α and β -Actin in primary human keratinocytes unstimulated or stimulated with TNF- α and untreated or treated with 1mM DMOG or 100 μ M JNJ1935 (n=4). (B) **below left**, relative luciferase units from primary human keratinocytes transfected with the HRE-Gluc HIF reporter and treated as described (n=4). (B) **below right** densitometry of western blots as described in C (n=4). (C-E) Supernatants obtained from human primary keratinocytes treated with 100 μ M JNJ1935 or vehicle for 1 hour and then stimulated with 50ng/ml TNF- α , were analyzed by ELISA to determine the amount of CXCL1 (C), CCL5 (D) and IL-8 (E). (F-H) RNA extracts from cultured human primary keratinocytes treated likewise were analyzed by qRT-PCR to evaluate the

relative amounts of CCL5 (F), CXCL1 (G) and IL8 (H) transcripts (n≥4), * means p≤0.05; ** means p≤0.01; *** means p≤0.001.

Figure 5. Hydroxylase inhibitors reduce *JNK phosphorylation in keratinocytes and increase caspases 3/7 activity in neutrophils*. **(A)** Supernatants obtained from human primary keratinocytes treated with Vehicle or JNJ1935 or BAY11-7082 or PD98059 or SP600125 or SB203580 for 4 hours and then stimulated with 50ng/ml TNF- α , were analyzed by ELISA to determine the amount of CCL5 (n=3). **(B)** representative western blot of HIF-1 α , pJNK and β -Actin in primary human keratinocytes untreated or treated with JNJ1935 for 1 hour and then stimulated with 50ng/ml of TNF α for 0.5, 2, 4 or 6 hours. **(C)** densitometry of pJNK from western blots described in C (n=3). **(D)** caspase 3/7 activity in HL-60 cells differentiated to neutrophils with 1 μ M ATRA and untreated or treated with 1mM DMOG for 2, 4, 8 or 24h. Etoposide was used as apoptotic control. **(E)** Scheme indicating the potential multifactor mechanism whereby hydroxylase inhibition reduces chemokine production in keratinocytes while it increases apoptosis in neutrophils. **means p≤0.01; ***means p≤0.001.

Figure 6. *Topical administration of DMOG reduces acute inflammation and neutrophil infiltration in DNFB-induced dermatitis*. **(A)** representative images of haematoxylin and eosin stained mouse ear cross-sections from mice untreated or treated with topical administration of 8mg/mouse DMOG for 1 hour and then challenged with vehicle or DNFB. **(B)** ear thickness quantification (reflecting ear swelling) at 8 hours post challenge in mice treated as described in a. **(C)** representative images of mouse ear cross-sections stained for DAPI/Ly6G/CXCR2 in mice treated as described in A. (n=5), ** means p≤0.01; *** means p≤0.001.