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An Anti-Inflammatory Role for Carbon Monoxide and Heme Oxygenase-1 in Chronic Th2-Mediated Murine Colitis

Shehzad Z. Sheikh,*†,1 Refaat A. Hegazi,‡,1 Taku Kobayashi,*† Joseph C. Onyiah,*† Steven M. Russo,*† Katsuyoshi Matsuoka,*† Antonia R. Sepulveda,§ Fengling Li,*† Leo E. Otterbein,§ and Scott E. Plevy*†

Cigarette smoking is one of the most significant environmental risk factors identified in the human inflammatory bowel diseases (IBD): Crohn’s disease (CD) and ulcerative colitis (UC). Meta-analyses showed that the risk for developing UC in current smokers is ∼40% that of nonsmokers (1). Former smokers have ∼1.7 times increased risk for developing UC (2). Some studies even suggested a dose response, with heavier smokers having greater protection (1). Based on these compelling epidemiological observations, one of the important unanswered questions in IBD is how does cigarette smoking mechanistically mediate this protective effect?

The gaseous molecule CO is one candidate that may contribute to the beneficial association between smoking and UC. CO is a prominent component of cigarette smoke: blood carboxyhemoglobin levels, a measure of systemic exposure to CO, were reported to range from 1–18% in active smokers (3). CO, best known as a toxic compound, is also produced endogenously during normal physiology by the heme oxygenase (HO) enzymes, which mediate the degradation of heme into equimolar quantities of CO, iron, and biliverdin. In particular, the enzyme HO-1 and its metabolic products regulate immune responses, tissue injury, and repair (4). We previously showed that CO ameliorates active inflammation in an experimental model of chronic IBD, IL-10–deficient (−/−) mice, through induction of HO-1 (5). CD4+ Th cells play a key role in the regulation of immune responses in the intestine. CD4+ T cells have been divided into functionally important subsets based on the cytokines that they produce (6). Although these subdivisions represent a reduction of complex biology, most applicable to the mouse, they provide a framework to understand mucosal T cell responses in human IBD. Th1 cells produce the cytokines IFN-γ and IL-2. Th1 cells are a hallmark of cell-mediated immunity, necessary for the eradication of intracellular pathogens and the development of long-term immunity against infectious agents (6). Numerous mouse models of IBD are characterized by an overabundance of intestinal Th1 cytokines. CD was initially described as a prototype Th1-mediated chronic inflammatory disorder, characterized by mucosal granulomas (the histological hallmark of a Th1 response), increased expression of IFN-γ, as well as increased IL-
12, a cytokine necessary for Th1 development (7). However, the discovery of the cytokine IL-23, which shares a common p40 subunit with IL-12, led to a paradigm shift in our understanding of inflammatory responses in IBD (8). IL-23, unlike IL-12, promotes a distinct CD4+ T cell activation profile, the Th17 cell, characterized by the production of the cytokine IL-17. A pivotal role for IL-23 and Th17 cells was demonstrated in experimental IBD models, such as the IL-10−/− mouse, and recent genetic and immunologic findings highlight the importance of this pathway in human IBD (9).

Th2 cells produce the cytokines IL-4, IL-5, and IL-13. These cytokines provide help for B cell Ab production, and are involved in host defense against extracellular helminthic parasites in the mucosal immune system (10). Inflammation in human UC has been characterized as mediated by Th2 cytokines. Lamina propria T cells from UC patients produce IL-13 and IL-5 and little IFN-γ (11). Although multiple experimental models of chronic Th1/17-driven intestinal inflammation have been elucidated, few have been described in which chronic disease occurs in a Th2 cytokine milieu. Mice with targeted disruption of the TCRγδ+ gene (TCRγδ−/−) perhaps most closely recapitulate the colonic Th2 signature in human UC. IL-4 and IL-13 play important roles in the development of colitis in TCRγδ−/− mice (12).

Our previous work showed that CO and HO-1 induction ameliorates Th17-mediated colonic inflammation in IL-10−/− mice (5). To model the protective effects of cigarette smoking in human UC, CO and the HO-1 pathway were studied in a murine model (13). Although multiple experimental models of chronic Th1/17-mediated colonic inflammation in IL-10−/− mice (12) were utilized, we observed that CO was protective, whereas HO-1 was beneficial.

Western immunoblots
Western blots were performed on whole-cell extracts, as described (15). Tissue from the ileocecal region was collected, homogenized, and thawed on the day of analysis. Protein concentration was determined by the bicinchoninic acid assay (Pierce), and equal amounts of protein were electrophoresed. Each band was visualized with the cell-based HO-1 ELISA (R&D Systems). CO-induced anti-inflammatory effects were also tested with Western immunobots (Western blotting).

Flow cytometry
Bone marrow-produced macrophages (BMMs) were cultured as described previously (5).

Colonic tissue explant cultures
Colonic tissue fragments (0.5 g dry weight) were processed, as previously described (14). Tissue-explant supernatants were collected after 24 h for cytokine ELISAs.

Isolation of colonic macrophages
Lamina propria mononuclear cells (LPCMs) were isolated from mouse colon by enzymatic method, followed by Percoll (GE Healthcare, Piscataway, NJ) density-gradient centrifugation, as previously described (15). LPCMs were further separated into CD11b+ cells using anti-CD11b microbeads (Miltenyi Biotec, Auburn, CA). Purity was >90% by flow cytometric analysis.

Histology
Histologic sections were stained with hematoxylin and eosin, and the severity of inflammation was assessed using a semi-quantitative scoring system. The following criteria were used: 0 = no inflammation; 1 = mild inflammation; 2 = moderate inflammation; and 3 = severe inflammation. The final score was the sum of the scores for each of the following parameters: inflammatory cell infiltration, goblet cell loss, and crypt architectural disruption. The severity of inflammation was then graded as 0 = none, 1 = mild, 2 = moderate, or 3 = severe.

Analysis
Statistical significance for data subsets from experiments performed in cells was assessed by the two-tailed Student’s t test. Statistical significance for
Results

CO exposure ameliorates active colitis in TCRα−/− mice

TCRα−/− mice were exposed to 250 ppm of CO from 12–16 wk of age (n = 10) and compared with a control group (n = 10) exposed to ambient air. Mice in both treatment groups were matched for age, sex, and initial body weight. CO-exposed mice showed an increase in body weight compared with mice housed in ambient air (Fig. 1A). Assessment of histological improvement was performed by a pathologist blinded to treatment groups. CO-exposed mice demonstrated significantly reduced histologic inflammation (Fig. 1B, Supplemental Fig. 1).

We next determined whether CO exposure affects colonic cytokine expression in TCRα−/− mice. Colonic explant cultures from TCRα−/− mice exposed to CO in vivo for 4 wk produced less IL-1β, IL-4, TNF, and IL-17 (Fig. 1C, 1D), correlating with histological improvement. CO treatment in vivo also resulted in increased colonic IL-10 secretion compared with explant cultures from air-exposed TCRα−/− mice (Fig. 1C).

Because IL-10 is an important regulatory cytokine, correlations between CO exposure and colonic IL-10 induction were further explored. Ten-week-old TCRα−/− mice were divided into three groups: group 1 was exposed to CO (250 ppm) for 4 wk, group 2 was exposed to air for 4 wk, and group 3 was exposed to CO for 2 wk and then transferred to ambient air for 2 wk. Mice exposed to CO demonstrated increased secretion of IL-10 in colonic explants. Mice transferred from CO exposure to air after 2 wk showed intermediate IL-10 secretion, with more colonic IL-10 compared with air-exposed mice but less than mice continually exposed to CO (Fig. 1E). These findings suggested that CO may ameliorate inflammation through induction of IL-10. Furthermore, because IL-10 secretion was still increased 2 wk after removing mice from CO, CO may induce a durable change in a cell population that secretes IL-10 in the colon.

CO induces IL-10 and HO-1 in colonic CD11b+ LPMCs

To elucidate potential mechanisms through which CO ameliorates experimental colitis, TCRα−/− mice were treated i.p. with ALF186 (30 mg/kg) and iALF186 (30 mg/kg) twice weekly for 2 wk. Colonic CD11b+ LPMCs, predominantly representing a macrophage cell population (14), were isolated from both groups, and Hmox1 and Il10 expression were analyzed. Hmox1 was induced in CD11b+ and CD11b− LPMCs in ALF186-treated TCRα−/− mice compared with iALF186-treated mice (Fig. 2A), with the most significant induction in CD11b+ cells. Interestingly, markedly increased Il10 expression was demonstrated in CD11b+ LPMCs, but not in CD11b− LPMCs, from ALF186-treated mice compared...
with iALF186-treated mice (Fig. 2B). No differences were observed in expression of surface markers (F4/80, CD80, CD86, and CD14) in CD11b+ LPMCs from TCRα/β− mice treated with ALF186 or iALF186 (Supplemental Fig. 2A). Similar results were obtained for Hmox1 and Il10 expression in LPMCs from ALF186-treated WT mice, with the exception that Il10 induction was also demonstrated in the CD11b− LPMC population (Supplemental Fig. 3), possibly reflecting increased numbers of CD4+ Foxp3+ lamina propri a T regulatory cells in WT mice compared with TCRα/β− mice (see later discussion; Supplemental Fig. 1C).

Another member of the IL-10 family of cytokines, IL-22, was shown to dampen innate mucosal inflammatory responses and attenuate colitis in TCRα/β− mice (19). LPMCs from ALF186-treated TCRα/β− mice demonstrated significantly more IL-22 (Il22) expression than did CD11b+ LPMCs from ALF186-treated mice, predominantly in the CD11b+ LPMC population, but in CD11b− cells as well (Fig. 2C).

Regulatory CD4+ Foxp3+ T and CD11d+ B cells were demonstrated to be a source of intestinal IL-10 production and have important anti-inflammatory roles in murine IBD (19). However, no differences in the numbers of CD11d+ B cells in LPMCs were found between iALF186- and ALF186-treated TCRα/β− mice (Supplemental Fig. 2B). Interestingly, a marked decrease in the numbers of splenic CD4+ Foxp3+ T cells was observed in TCRα/β− mice compared with WT mice (Supplemental Fig. 2C), and Foxp3+ cells were undetectable in LPMCs from TCRα/β− mice (data not shown). These results suggested that CO may be protective in experimental colitis through induction of IL-10 and HO-1, specifically in CD11b+ LPMCs.

**CO induces IL-10 in macrophages through induction of HO-1**

To further elucidate regulation of IL-10 by CO in macrophages, WT and TCRα/β− BMMs were stimulated with LPS in CO (250 ppm) or ambient air for 24 h. As previously described (13), CO-augmented LPS stimulated IL-10 secretion in WT BMMs (Fig. 3A) (5). CO also augmented IL-10 secretion from LPS-stimulated TCRα/β− BMMs (Fig. 3B). However, in LPS-activated BMMs from HO-1−deficient (Hmox1−/−) mice, CO failed to induce IL-10 secretion (Fig. 3C), suggesting that CO augments IL-10 secretion through an HO-1−dependent signaling pathway. Moreover, WT BMMs incubated with ALF186 (100 µg/ml) for 3 h demonstrated significantly increased basal Hmox1 and Il10 expression compared with iALF186 BMMs (Fig. 3D, 3E).

**HO-1 induction recapitulates immunomodulatory effects of CO in vivo**

To understand the role of HO-1 in the anti-inflammatory effects of CO in vivo, TCRα/β− mice were treated with a pharmacological inducer of HO-1, CoPP (5 mg/kg i.p.), twice a week for 2 wk and compared with vehicle (DMSO)-treated controls. CoPP treatment resulted in improved histological scores compared with vehicle treatment (Fig. 4A). Moreover, colonic explant cultures revealed decreased IL-4 (Fig. 4B), IL-1β, TNF, and IL-17 (Fig. 4C) secretion in CoPP-treated TCRα/β− mice. CoPP treatment also resulted in robust induction of Hmox1 expression in colonic CD11b− and CD11b+ LPMC populations (Fig. 4D). Colonic CD11b+ LPMCs were the primary source of IL-10 secretion from CoPP-treated TCRα/β− mice, because less IL-10 expression was observed in CD11b− cells (Fig. 4E). These results strongly implicated CD11b+ LPMCs as the primary source of IL-10 in TCRα/β− mice and important targets for the immunomodulatory effects of CO and HO-1.

Next, to address whether immunomodulatory effects of CO are mediated by HO-1 in vivo, TCRα/β− mice were treated i.p. with ALF186, with or without the HO-1 inhibitor SnPP. ALF186-treated mice demonstrated reduced histologic inflammation compared with ALF186+SnPP-treated mice (Fig. 5A). Importantly, CD11b+ LPMCs from ALF186+SnPP-treated TCRα/β− mice expressed significantly less Il10 than did CD11b+ LPMCs from ALF186-treated mice (Fig. 5B). Likewise, CD11b− and CD11b+ LPMCs from ALF186+SnPP-treated TCRα/β− mice demonstrated lower Il22 expression than did LPMCs from ALF186-treated mice (Fig. 5C). These findings demonstrated that the anti-inflammatory effects of CO are abrogated in the presence of an HO-1 inhibitor.

**LPS and IL-10 regulate HO-1 expression in macrophages**

Because HO-1 is required for the protective effects of CO, we next studied HO-1 (Hmox1) regulation in macrophages. BMMs from WT and IL-10−/− mice were stimulated with LPS, with or without IL-10, and expression of Hmox1 mRNA and HO-1 protein was determined. IL-10−/− BMMs demonstrated decreased expression of Hmox1 compared with WT BMMs. Addition of rIL-10 restored Hmox1 mRNA and protein expression in LPS-activated IL-10−/− BMMs and augmented Hmox1 expression in WT BMMs (Fig. 6A, 6B). Moreover, incubation of WT BMMs with an IL-10 Ab inhibited LPS-induced expression of HO-1. These results demonstrated that LPS and IL-10 are regulators of HO-1 in macrophages.

TLRs recognize specific molecular patterns present in a broad range of microbial pathogens. TLR activation uses a common signal-transduction pathway initiated by the adaptor protein MyD88. To further elucidate TLR-mediated induction of HO-1, WT and MyD88−/− BMMs were stimulated with MyD88-dependent (sBLP, LPS, flagellin, and CpG DNA) bacterial ligands. Interestingly, sBLP, LPS, flagellin, and CpG DNA induced HO-1 expression in WT BMMs but not in MyD88−/− BMMs (Fig. 6C). Addition of rIL-10 restored HO-1 expression in MyD88−/− BMMs, suggesting that IL-10–induced expression of HO-1 in macrophages is independent of TLR/MyD88-signaling pathways. As previously reported, TLR-mediated IL-10 expression, another
MyD88-dependent gene, was abrogated in MyD88<sup>−/−</sup> BMMs (Supplemental Fig. 4).

The transcription factor Nrf2 is a critical regulator of HO-1 through binding to antioxidant response elements (20). In the absence of MyD88, Nrf2 protein expression in macrophages was also markedly reduced (Fig. 6C). These results elucidated a novel regulatory circuit, with MyD88-dependent Hmox1 expression by bacterial products, in part through Nrf2, and MyD88-independent regulation by IL-10.

**Discussion**

In summary, CO exposure ameliorates chronic Th2-mediated colitis in TCRα<sup>−/−</sup> mice. Immunomodulatory effects of CO were recapitulated by pharmacologic HO-1 induction. Moreover, pharmacologic inhibition of HO-1 blocked the protective effects of CO on colitis, suggesting that in vivo, CO mechanistically requires HO-1 function. CO and HO-1 induction resulted in increased colonic IL-10 expression prominently in CD11b<sup>+</sup> LPMCs, with consequent inhibition of inflammatory cytokines. We previously demonstrated that CO ameliorated colitis in IL-10<sup>−/−</sup> mice (5). IL-10<sup>−/−</sup> mice exhibit a Th17-mediated immune pathology. The protective effects of CO in IL-10<sup>−/−</sup> mice were attributed, in part, to inhibition of the common p40 subunit of the inflammatory cytokines IL-12 and IL-23 (5). Our current study elucidated the anti-inflammatory effects of CO and the HO-1 pathway in TCRα<sup>−/−</sup> mice characterized by a distinctly different immunopathogenesis, with increased colonic Th2 cytokine expression that, to some extent, recapitulates the colonic inflammatory cytokine milieu in human UC (12). This study further elucidated pleiotropic immunomodulatory effects of CO and the HO-1 pathway. There are now illustrations of therapeutic applications of this pathway (5, 21, 22) in multiple experimental models of IBD mediated by divergent immune mechanisms. Given the genetic, immunologic, and clinical heterogeneity of the human IBDs, the therapeutic benefit of CO and HO-1 in numerous preclinical models suggests potentially broad applications in patients.

Notably, in TCRα<sup>−/−</sup> mice, CO- and HO-1–mediated inhibition of inflammation correlated with increased levels of the anti-inflammatory cytokine IL-10. Cross-talk between CO/HO-1 and IL-10 regulation may underlie the homeostatic function of each modality. Lee and Chau (23) demonstrated that IL-10 induced the expression of HO-1 via a p38 MAPK-dependent pathway. IL-10–induced expression of HO-1 also requires activation of STAT-3 (24). Moreover, HO-1 may be an important downstream mediator of the anti-inflammatory effects of IL-10 in macrophages. HO-1 activity and the generation of endogenous CO were necessary for IL-10–dependent inhibition of TNF expression (25). Likewise, LPS-activated macrophages overexpressing HO-1 or exposed to CO demonstrated reduced TNF production, whereas IL-10 secretion was enhanced (26). Interestingly, we demonstrated that LPS stimulated HO-1 expression in WT BMMs, but not IL-10<sup>−/−</sup> BMMs, and blocking IL-10 diminished LPS-activated HO-1 expression. Hence, IL-10 is a cofactor for HO-1 induction by TLR ligands. Moreover, Hmox1 induction occurred through MyD88-dependent (bacterial products) and -independent (IL-10) pathways. LPS and inflammatory cytokines (IL-1β and TNF) are well described as potent inducers of HO-1, and several studies linked NF-κB and AP-1 transcription factors in this response (27, 28). However, given the absence of a clearly identified functional NF-κB element, how NF-κB promotes Hmox1 gene transcription is a matter of speculation (29–31). Nrf2, a basic leucine zipper transcription factor, is involved in cellular protection against...
oxidative stress through antioxidant response element-directed induction of multiple detoxifying and antioxidant enzymes, including HO-1 (20). We demonstrated defective induction of Nrf2 in MyD88−/− BMMs, suggesting a mechanism for how TLR signaling may affect Hmox1 transcription.

HO-1 was also shown to exert its protective effect in experimental asthma through a mechanism mediated by IL-10 expression in CD4+CD25+Foxp3+ T regulatory cells (32). In vivo CO exposure ameliorated intestinal injury induced by LPS or ischemia–reperfusion. Mucosal levels of IL-10 were shown to be increased in CO-exposed mice (33). Similarly, CO-releasing molecules promoted resolution of acute pancreatic inflammation in rats, which correlated with increases in local IL-10 expression (34). CO was also shown to augment local IL-10 and afford protection in other models of inflammation, including sepsis, renal injury, and diabetes (35–37).

Activated macrophages are an abundant source of IL-10 (38). CO augments basal and LPS-induced IL-10 secretion from WT and TCRα−/− BMMs. Specifically, TCRα−/− mice treated with CO and CoPP demonstrated a specific increase in IL-10 secretion.

**FIGURE 4.** The HO-1 inducer CoPP ameliorates colitis in TCRα−/− mice. Twelve-week-old TCRα−/− mice were treated with i.p. injection of CoPP (5 mg/kg, twice a week for 2 wk) (n = 8), and control mice were treated with DMSO vehicle i.p. (n = 12). A, CoPP-injected mice had less severe colitis. B, Spontaneous protein secretion determined in 24-h supernatants from colonic explants from CoPP-treated (5 mg/kg) and vehicle-treated (DMSO) TCRα−/− mice. C, Spontaneous IL-4 was determined by cytokine-specific ELISA, and IL-1β, TNF, and IL-17 secretion were determined by Linco 16-multiplex cytokine assay. Bars represent mean ± SEM from 12 mice per group. D, LPMCs were isolated from colons of TCRα−/− mice treated with CoPP (black bars) and vehicle (white bars), separated into CD11b− and CD11b+ cells, and analyzed for Hmox1 expression by real-time RT-PCR, with results normalized to β-actin. E, IL-10 secretion was determined by ELISA. Each result represents the mean ± SEM of triplicate assays from four mice per treatment group. *p < 0.05 versus vehicle-treated mice.

**FIGURE 5.** Hmox1 function is required for amelioration of colitis and Il10 and Il22 upregulation by CO in TCRα−/− mice. A, Colitis scores were significantly higher in iALF-186 (n = 6) ALF186+ SnPP (50 μM/kg twice/weekly for 2 wk) (n = 6) treated mice compared with mice treated with ALF186 alone (n = 6). B and C, LPMCs were isolated from colons of TCRα−/− mice treated with ALF186 (n = 6) or ALF186+SnPP (n = 6). They were separated into CD11b− and CD11b+ cells and analyzed for Il10 (B) and Il22 (C) expression by real-time RT-PCR. Results were normalized to β-actin. Bars represent mean ± SEM triplicate cultures from pooled LPMCs from six mice per group. *p < 0.05 versus iALF186-treated TCRα−/− mice and CD11b+ LPMCs.
were stimulated with LPS (100 ng/ml) in the presence of IL-10 (10 ng/ml) for 24 h after initial preincubation with anti–IL-10 Ab (10 ng/ml) for 1 h. HO-1 protein was analyzed by Western blotting. Data are representative of three independent experiments.

Regulation of HO-1 in macrophages is IL-10 and MyD88 dependent. A. WT and IL-10−/− BMMs were stimulated with LPS alone (100 ng/ml) or with LPS plus IL-10 (10 ng/ml) for 12 h. Total RNA was isolated and analyzed for Hmox1, and β-actin mRNA expression was detected by real-time RT-PCR. Results are expressed as mean ± SEM from three independent experiments. *p < 0.05 versus LPS-treated WT BMMs. B. WT and IL-10−/− BMMs were stimulated with LPS (100 ng/ml) in the presence of IL-10 (10 ng/ml) for 24 h after initial preincubation with anti–IL-10 Ab (10 μg/ml) for 1 h. HO-1 protein was analyzed by Western blotting. Data are representative of five independent experiments with similar results. C. WT and MYD88−/− BMMs were stimulated with LPS (100 ng/ml), CpG (1 μM), sBLP (100 ng/ml), flagellin (10 ng/ml), or IL-10 (10 ng/ml) for 24 h. HO-1 and Nrf2 protein was analyzed by Western blotting. Data are representative of three independent experiments.

FIGURE 6. Regulation of HO-1 in macrophages is IL-10 and MyD88 dependent. A. WT and IL-10−/− BMMs were stimulated with LPS alone (100 ng/ml) or with LPS plus IL-10 (10 ng/ml) for 12 h. Total RNA was isolated and analyzed for Hmox1, and β-actin mRNA expression was detected by real-time RT-PCR. Results are expressed as mean ± SEM from three independent experiments. *p < 0.05 versus LPS-treated WT BMMs. B. WT and IL-10−/− BMMs were stimulated with LPS (100 ng/ml) in the presence of IL-10 (10 ng/ml) for 24 h after initial preincubation with anti–IL-10 Ab (10 μg/ml) for 1 h. HO-1 protein was analyzed by Western blotting. Data are representative of five independent experiments with similar results. C. WT and MYD88−/− BMMs were stimulated with LPS (100 ng/ml), CpG (1 μM), sBLP (100 ng/ml), flagellin (10 ng/ml), or IL-10 (10 ng/ml) for 24 h. HO-1 and Nrf2 protein was analyzed by Western blotting. Data are representative of three independent experiments.

exclusively from CD11b+ LPMCs, which include a predominant resident macrophage population. These findings expand upon an important homeostatic role for IL-10–producing colonic macrophages, which act on T regulatory cells to maintain expression of Foxp3 in a T cell adoptive-transfer model of murine colitis (39).

Several regulatory B cell populations have been characterized in TCRα−/− mice. A subset of regulatory B cells was identified as an important source of IL-10 and was responsible for inhibiting IL-1β and ameliorating colitis (40). However, we could not discern any difference in the numbers of CD1d+ MLNs from ALF186-treated TCRα−/− mice compared with iALF186-treated mice. An IL-12–producing regulatory B cell subset that develops in the presence of IL-10 was also shown to be involved in the regulation of colonic inflammation in this model (41). During CO exposure and pharmacologic HO-1 induction in vivo, IL-10 is almost exclusively detected in the CD11b+ LPMC fraction. These findings suggested that CO and HO-1 induction, mediated in part through IL-10, has anti-inflammatory effects that extend beyond the induction of previously described regulatory B cell populations in this model.

Colonic Foxp3+ cells were not detected in ALF186- or iALF186-treated TCRα−/− mice. Moreover, a significant deficiency of splenic CD4+Foxp3+ T cells was observed in TCRα−/− mice compared with WT mice. The TCR was shown to be involved in the development of CD4+Foxp3+ T cells (42); however, the influence of TCRα-chain repertoire on the development of CD4+ Foxp3+ T cells has not been analyzed. TCRα-chain expression is not essential for CD4+CD25+ T cell development, but its effect on Foxp3 expression remains unknown (43). Although the purpose of our study was not to discern T regulatory cell development in TCRα−/− mice, taken as a whole, our results suggested that the predominant source of IL-10 in LPMCs from TCRα−/− mice, and therefore a target for CO and HO-1 induction, resides in the CD11b+ population and not Foxp3+ T cells.

We unexpectedly detected a Th17-cytokine signature in colonic explants from TCRα−/− mice with abundant levels of IL-17. The IL-17–producing cell population(s) remain(s) to be determined.

Given recent reports, it is interesting to speculate that γδ T cells may be a source of IL-17 (44). Interestingly, IL-17 levels decreased following CO exposure or HO-1 induction, correlating with histologic improvement. Recently, the IL-10 family member IL-22, expressed by Th17 cells, was demonstrated to ameliorate colitis in TCRα−/− mice (19). CO-treated TCRα−/− mice demonstrated significant increases in IL-22 mRNA expression in CD11b− LPMCs, consistent with previous studies suggesting that nonmacrophage-derived IL-22 may also be involved in the protective effects of CO/HO-1. Notably, IL-22 is a potent inducer of IL-10 (19). The description of a Th17 signature in TCRα−/− mice also substantiated this as a model for human UC, in which the same genetic associations within the IL-23/Th17 pathway confer susceptibility to CD and UC (45). Likewise, current biological interventions that inhibit TNF are approved for the treatment of moderate to severe UC (46). CO and pharmacological induction of HO-1 resulted in a significant decrease in TNF secretion in TCRα−/− colons, which may also mediate therapeutic effects.

To our knowledge, these results are the first to characterize anti-inflammatory properties of CO and HO-1 in a Th2-mediated model of chronic colonic inflammation. The anti-inflammatory effects of CO are attributed to the induction of HO-1 and highlight the broad impact of these pathways in intestinal inflammation. HO-1 induction correlated with increased IL-10 and IL-22 expression in vivo, which may be relevant anti-inflammatory mechanisms of this pathway, because both cytokines were previously determined to have a protective role in colonic inflammation in TCRα−/− mice (19, 41). It remains to be determined whether HO-1 induction mediates downstream anti-inflammatory effects in colitis models through increased enzymatic activity and production of endogenous metabolic products, including CO, or through other mechanisms. Nonetheless, these experiments demonstrated that HO-1 is a central regulator of intestinal homeostasis through pleiotropic mechanisms and that understanding these pathways are of mechanistic and therapeutic relevance in human IBD.
Disclosures

L.O. is a scientific consultant for Alfama, Inc., and provided CO-releasing molecules (ALF186) for some experiments. The other authors have no financial conflicts of interest.

References

SUPPLEMENTAL FIGURE LEGENDS

Supplemental Figure 1. CO ameliorates histologic colitis in TCRα⁻/⁻ mice. TCRα⁻/⁻ mice were housed in ambient air or a chamber maintaining a constant concentration of CO at 250 ppm (n=10 each) from 12 to 16 weeks of age. Representative hematoxylin and eosin staining and depiction of histologic colitis of TCRα⁻/⁻ colonic tissues. Top panel, ambient air; Bottom panel, CO-treated (magnification at 40X). Colons of inflamed 16 week old TCRα⁻/⁻ mice housed in ambient air have elongated crypts, thickened mucosal and submucosal layers with transmural inflammation compared to CO exposed mice. Infiltrates are predominantly lymphocytes and monocytes with few neutrophils.

Supplemental Figure 2. Surface marker expression in mononuclear cell populations from TCRα⁻/⁻ mice. Colonic LPMCs from ALF186 (30 mg/kg) and iALF186 (30 mg/kg) treated TCRα⁻/⁻ mice were labeled with antibodies against (A) macrophage activation markers, F4/80, CD14, CD80 in CD11b⁺ gated LPMCs (B) CD1d expression for B cells gated on B220⁺ LPMCs. Dead cells were excluded with propidium iodide staining. Representative staining patterns of LPMCs harvested from 4 individual mice is shown. (C) Splenocytes from WT and TCRα⁻/⁻ mice were isolated and pooled (n=3) and were labeled with antibodies against CD4 followed by intracellular cytokine staining for FoxP3. Representative pattern of splenocyte staining from 3 individual mice is shown.

Supplemental Figure 3. Hmox and Il10 induction in LPMC from CORM-186 treated WT mice. LPMCs were isolated from colons of WT mice treated with inactive CO-releasing molecule 186 (iALF186, n=4, white bars) and ALF186 (n=4, black bars). LPMCs were further separated into CD11b⁻ and CD11b⁺ cells and analyzed for (A) Hmox1 (B) and Il10 expression by real-time RT-PCR. Results were normalized to β-actin. Error bars represent mean±SEM triplicate cultures from pooled LPMCs from
four mice per group. p<0.05 vs. iALF186 treated CD11b⁺ LPMCs.

**FIGURE 4. Regulation of IL-10 in macrophages is MyD88 dependent.** WT and MYD88⁻⁻ BMMs were stimulated with LPS (100 ng/mL), CpG (1 μM), SbLP (100 ng/mL), and flagellin (10 ng/mL) for 24 hours. IL-10 protein was analyzed by ELISA. Data is representative of 3 independent experiments. Error bars represent mean±SEM from 3 independent experiments. p<0.05 vs. WT simulated BMMs.
Supplemental Figure 2
Supplemental Figure 3

A

Hmox1 mRNA fold induction

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B

Il10 mRNA fold induction

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Supplemental Figure 4