Carbon monoxide–based therapy ameliorates acute pancreatitis via TLR4 inhibition

Jing Xue, Aida Habtezion


The protective role of hemeoxygenase-1 (HO-1) in various inflammatory conditions is mediated in part by its products, carbon monoxide (CO) and biliverdin. Here we investigated a therapeutic role for CO and CO-primed cells in acute pancreatitis (AP). In a mouse model of AP, treatment with CO-releasing molecule–2 (CORM-2) decreased mortality, pancreatic damage, and lung injury. CORM-2 decreased systemic inflammatory cytokines, suppressed systemic and pancreatic macrophage TNF-α secretion, and inhibited macrophage TLR4 receptor complex expression. In both human and mouse cells, CORM-2 inhibited endogenous and exogenous ligand-dependent TLR4 activation, which indicates that CORM-2 could be therapeutic for both early and late stages of AP, which involve sterile- and endotoxin-mediated inflammation, respectively. Mice engrafted with TLR4-deficient hematopoietic cells were protected against caerulein-induced AP. In the absence of leukocyte TLR4 expression, CORM-2 did not confer additional protection, which indicates that CORM-2–dependent effects are mediated via suppression of macrophage TLR4 activation. We determined that CO was directly responsible for the protective effects of CORM-2 in AP, as inactive forms of CORM-2 were ineffective. Importantly, adoptive transfer of CORM-2–primed cells reduced AP. Such a therapeutic approach would translate the beneficial effects of CO-based therapies, avoiding CO- or CO-RM–mediated toxicities in AP and a wide range of diseases.

Find the latest version:

https://jci.me/71362/pdf
Carbon monoxide–based therapy ameliorates acute pancreatitis via TLR4 inhibition

Jing Xue and Aida Habtezion
Department of Medicine, Division of Gastroenterology and Hepatology, Stanford University School of Medicine, Stanford, California, USA.

The protective role of heme oxygenase-1 (HO-1) in various inflammatory conditions is mediated in part by its products, carbon monoxide (CO) and biliverdin. Here we investigated a therapeutic role for CO and CO-primed cells in acute pancreatitis (AP). In a mouse model of AP, treatment with CO-releasing molecule–2 (CORM-2) decreased mortality, pancreatic damage, and lung injury. CORM-2 decreased systemic inflammatory cytokines, suppressed systemic and pancreatic macrophage TNF-α secretion, and inhibited macrophage TLR4 receptor complex expression. In both human and mouse cells, CORM-2 inhibited endogenous and exogenous ligand-dependent TLR4 activation, which indicates that CORM-2 could be therapeutic for both early and late stages of AP, which involve sterile- and endotoxin-mediated inflammation, respectively. Mice engrafted with TLR4-deficient hematopoietic cells were protected against caerulein-induced AP. In the absence of leukocyte TLR4 expression, CORM-2 did not confer additional protection, which indicates that CORM-2–dependent effects are mediated via suppression of macrophage TLR4 activation. We determined that CO was directly responsible for the protective effects of CORM-2 in AP, as inactive forms of CORM-2 were ineffective. Importantly, adoptive transfer of CORM-2–primed cells reduced AP. Such a therapeutic approach would translate the beneficial effects of CO-based therapies, avoiding CO- or CO-RM–mediated toxicities in AP and a wide range of diseases.

Introduction
Carbon monoxide (CO) is increasingly recognized as a cytoprotective and homeostatic molecule with important signaling capabilities in physiologic and pathophysiologic situations (1). CO is 1 of 3 products generated from heme degradation by the rate-limiting enzyme heme oxygenase–1 (HO-1) (2). The antiinflammatory and protective properties of CO are supported by accumulating evidence in animal models of cardiovascular disease, inflammatory disorders, and organ transplantation (3–6).

Transition metal carbonyls, termed CO-releasing molecules (CO-RMs), have been used in biological systems to deliver CO in a controlled manner while keeping carboxyhemoglobin levels stable. The first compound to corroborate the feasibility of this technology was the lipid-soluble metal carbonyl complex tricarbonyl dichlororuthenium (II) dimer ([Ru(CO)₃Cl₂]; also known as CORM-2). CORM-2 is able to transfer CO spontaneously and can exert typical CO-mediated pharmacologic effects (7). CO is released rapidly from CORM-2 once in solution with a half-life of about 20 minutes, and each mole of CORM-2 liberates approximately 0.7 mol CO (7).

One of the most feared complications of acute pancreatitis (AP) is infection and bacterial colonization of the necrotic pancreas, which leads to a significant rise in mortality. TLR4 activation is one of the mechanisms by which bacterial translocation may account for the development of severe experimental AP (8). Classically, the danger-associated molecules sensed by TLRs are highly conserved pathogen-associated molecular patterns expressed by bacteria and other pathogens that are not present in mammalian cells. However, numerous more recent reports have suggested that diverse molecules of host-cell origin may also serve as endogenous ligands for TLRs. In the case of TLR4, endogenous ligands such as heat shock proteins (HSPs), high-mobility group box protein 1 (HMGB1), and molecules from necrotic or dying cells have been proposed (9–11). Since AP progression and severity is associated with significant cell death and necrosis, such endogenous ligands are likely to play an important role in TLR4 activation (8, 12). In the present study, we investigated the therapeutic role of CO in experimental AP and its effect on TLR4 activation by exogenous and endogenous ligands using mouse and human cells. Using BM chimeras, we determined the contribution of immune cell TLR4 and the effect of CO therapy in AP. In addition, as a way of avoiding toxicities associated with systemic CO therapy, we tested the therapeutic utility of ex vivo CORM-2–primed cells.

Results
CORM-2 ameliorates established experimental AP. To determine the therapeutic effects of CORM-2, we used 2 independent mouse models of AP: caerulein hyperstimulation, which causes mild to moderate AP, and choline-deficient diet supplemented with DL-ethionine (CDE) feeding, which causes severe hemorrhagic AP associated with significant mortality. Mice were given CORM-2 or vehicle (VE) at 24 hours after starting CDE feeding, and serum and tissues (pancreas and lung) were harvested at 72 hours (Figure 1A). CORM-2 recipients had significantly lower mortality than VE recipients (Figure 1B). Single-dose CORM-2 dramatically suppressed serum amylose and lipase elevations (Figure 1, C and D). Pancreatic injury, as determined by histology scores and trypsin activity, was significantly lower in CORM-2–treated mice (Figure 1, E–G). CORM-2 additionally protected against pancreatic-associated distant lung injury, as shown by decreased lung myeloperoxidase (MPO) levels (Figure 1H). Similarly, CORM-2 was also effective in treating caerulein-induced AP (Supplemental Figure 1; supplemental material available online with this article; doi:10.1172/JCI71362DS1). We revealed the protective effect of CORM-2 in AP to be mediated by CO release, as 2 of its inactive...
forms — inactivated CORM-2 (iCORM-2), in which CO is depleted, and RuCl₃, which does not contain CO and is thus unable to release it — were ineffective (Supplemental Figure 2).

CORM-2 suppresses systemic proinflammatory cytokines and TNF-α production by spleen and pancreatic macrophages. AP is not only a localized disease, but is also associated with systemic inflammatory response. Thus, we assessed the effect of CORM-2 on circulating cytokines and found that CORM-2 treatment significantly decreased the serum proinflammatory cytokines TNF-α, IL-1α, IL-6, and IL-12p40 (Figure 2A). Activated leukocytes during the early phase of pancreatitis release cytokines, which in turn mediate and enhance the inflammatory cascade observed in AP. In particular, TNF-α plays a critical and central role in the pathogenesis of AP and recruitment of inflammatory cells. Since monocyte/macrophages are major source for TNF-α, we isolated spleen and pancreas leukocytes from VE- versus CORM-2–treated mice and tested their ability to respond to TLR4 activation using LPS. Consistent with the systemic and local inflammatory-suppressive effects, CORM-2 treatment significantly reduced TNF-α production by the lineage-negative (Lin−; i.e., CD3−CD19−NK1.1−) CD11b+CD11c−F4/80+ macrophage populations in the spleen and pancreas (Figure 2, B and C).

CORM-2 inhibits TLR4-mediated TNF-α production in mouse and human monocyte/macrophages. To further investigate the effect of CORM-2 on TLR4 signaling, we examined TNF-α production by spleen macrophages isolated from unmanipulated WT and TLR4-deficient (TLR4 KO) mice. CORM-2 inhibited both basal and LPS-induced TNF-α production by WT macrophages, but, as expected, it had no effect on TLR4 KO macrophages (Figure 3A). To determine whether the observed effects of CORM-2 are applicable to endogenous TLR4 ligands, we used S100 calcium-binding protein A8 (S100A8) and HMGB1 to activate TLR4 (13). Previous reports have shown direct binding of these endogenous ligands to the TLR4/myeloid differentiation 2 (TLR4/MD2) com-

Figure 1
CORM-2 treats CDE-induced AP. (A) Balb/c mice were treated with 8 mg/kg CORM-2 or VE control i.v. 24 hours after CDE feeding, then sacrificed at 72 hours. (B) Mouse survival over time. (C and D) Amylase (C) and lipase (D) results from sera collected at 72 hours. (E) Representative H&E-stained pancreatic sections. ED, edema; N, necrosis; Hem, hemorrhage. Scale bar: 100 μm. (F) Pancreas histology scores. (G) and (H) Pancreatic trypsin activity (G) and lung MPO measurements (H). Data are mean ± SEM of at least 3 independent experiments (n ≥ 5 per group).
plex via surface plasmon resonance studies (14, 15). Similar to our findings with LPS, S100A8-mediated TNF-α production by mouse BM-derived macrophages (BMDMs) was significantly suppressed by CORM-2 treatment (Figure 3B). We confirmed TLR4’s requirement for S100A8 using WT and TLR4 KO BMDMs with experiments similar to those in Figure 3A (data not shown). In order to address the translation potential of our study, we used human PBMCs and confirmed that CORM-2 suppressed LPS- and HMGB1-mediated TNF-α production by circulating human CD14+ monocytes (Figure 3C).

CORM-2 reduces macrophage TLR4/MD2 receptor complex expression during AP. A robust TLR4 response to LPS requires additional components of the LPS recognition complex, which includes CD14 and MD2 (16). MD2 directly recognizes the lipid A domain of LPS and activates TLR4/MD2 complex formation, which is necessary for cellular response and downstream signaling. Previously, using an insulinoma cell line, Rocuts et al. showed that CO suppresses membrane activation of TLR4 by blocking TLR4 glycosylation and the physical interaction between TLR4 and MD2 (17). To understand the mechanism by which CORM-2 negatively regulates TLR4 activation in AP, we compared macrophage TLR4/MD2 receptor complex expression in mice treated with VE versus CORM-2. Using the mAb MTS510, which recognizes TLR4/MD2 receptor complex but not TLR4 alone, we found a significant decrease in pancreatic macrophage TLR4/MD2 receptor complex expression in CORM-2–treated mice at both 48 and 72 hours after CDE feeding (Figure 4, A and B). In addition, we used the murine macrophage cell line RAW264.7 to assess the effect of CORM-2 on membrane total TLR4 and TLR4/MD2 receptor complex expression using the specific mAbs UT51 and MTS510, respectively. CORM-2 suppressed surface TLR4/MD2 expression, but had no effect on surface total TLR4 expression (Figure 5A). We also observed suppressive effects of CORM-2 on surface TLR4/MD2 expression and FITC-LPS binding using freshly isolated mouse peritoneal macrophages (Figure 5C). iCORM-2 had no effect on TLR4/MD2 expression and was not as effective in decreasing FITC-LPS binding (Figure 5C), which suggests that the inhibitory function of CORM-2 was mediated through CO release. Taken together, our data indicate that CORM-2 inhibits TLR4/MD2 complex formation, a process that is required for functional TLR4 receptor activation.

Ablation of TLR4 in hematopoietic cells confers protection against AP. Sharif et al. showed significantly less severe AP in TLR4 KO compared with WT mice (8). TLR4 is also expressed in nonhematopoietic pancreatic cells, such as epithelium of the pancreatic duet
In order to determine the contribution of and CORM-2’s effect on hematopoietic TLR4 in AP, we generated chimeric mice by engrafting WT recipients with either WT or TLR4 KO BM cells (WT → WT or TLR4 KO → WT mice, respectively). At 8 weeks after engraftment, mice underwent caerulein-induced AP and were treated as above with either VE or CORM-2 (Figure 6A). VE-treated WT → WT mice had significantly more pancreatic injury than their CORM-2–treated counterparts (Figure 6, B–F). CORM-2 treatment protected WT → WT mice similar to the results seen in nonengrafted WT mice (Supplemental Figure 1). In contrast, the pancreatic injury of VE-treated TLR4 KO → WT mice was not as severe as that of VE-treated WT → WT mice. Furthermore, the protective function of CORM-2 was only observed in WT → WT mice, not in TLR4 KO → WT mice (Figure 6, B–F). These results indicate that the protective effect of CORM-2 in AP is mediated by inhibition of hematopoietic TLR4 activation. CORM-2 did not have a significant effect on isolated primary acinar cells, as assessed by caerulein-mediated NF-κB activation, amylase secretion, and calcium influx (Supplemental Figure 3).

CORM-2–primed cells ameliorate experimental AP. Given the potential toxicity of systemically administered CO-RMs or CO, we tested whether monocytes/macrophages primed via CORM-2 pretreatment can transfer protection and treat AP, using an adoptive cell transfer model to treat caerulein-induced pancreatitis (Figure 3).
Compared with VE-primed CD11b+ cells, CORM-2–primed cells were more effective in protecting against caerulein-induced AP (Figure 7, B–F). CORM-2–primed cells downregulated mRNA expression of the proinflammatory *Tnfa* and upregulated expression of the antiinflammatory *Il10* and *Il22* (Figure 7G). To address whether the CORM-2–primed cells ameliorate AP via cotransfer of CORM-2, we tested the transferred cells and the media in which they were cultured for the presence of ruthenium and the ability to release CO using inductively coupled plasma mass spectrometry (ICP-MS) and myoglobin assay, respectively. There was no active or inactive CORM-2 transferred with the cells, and the ruthenium remained in the culture media (Supplemental Figure 4). Taken together, these findings showed that CORM-2–primed CD11b+ cells can transfer protection to mice undergoing AP and suggest that the therapeutic role of CORM-2 is mediated at least in part by monocytes/macrophages (CD11b+ cells) that express higher levels of IL-10 and IL-22.

**Discussion**

Despite significant morbidity and mortality, AP remains a clinical challenge, and no approved active therapies for this disease currently exist. We previously showed that HO-1 induction protects against experimental AP (19, 20). HO-1 is a rate-limiting enzyme that degrades heme into biliverdin, CO, and iron (2). The protective and antiinflammatory roles of HO-1 are thought to be mediated by the products biliverdin and CO (21). In agreement with this, we recently reported protective effects of biliverdin in AP that are mediated by downstream aryl hydrocarbon receptor activation and IL-22 induction (22). The unmet need for AP therapy and the limited understanding of the underlying immune responses in AP led us to explore the role of CO in AP and investigate potential mechanisms of action for CO.

To determine the therapeutic role of CO, we first established AP in mice using 24 hours of CDE feeding, as in our previous studies (19), and then treated the mice with either VE or CORM-2. CORM-2 was effective in treating local (pancreas), distant (lung), and systemic inflammatory effects of AP. Similar protective effects were also seen with the caerulein model of AP. Our results are consistent with the study by Chen et al. showing a protective effect of CORM-2 in a sodium taurocholate rat model of AP (23). Since the mechanisms for the beneficial and therapeutic effects of CORM-2 in AP are unknown, our next objective was to investigate potential mechanisms and identify CORM-2–mediated cellular targets.

Monocytes/macrophages play a central role in the pathogenesis of AP, and the degree of macrophage activation is one of the important factors that may determine AP severity (24). We previously showed that HO-1–overexpressing macrophages could transfer protection in experimental AP (20, 25). Thus, we postulated that CO, a downstream antiinflammatory product of HO-1, is likely to modulate monocyte/macrophage activation in AP. In support of this hypothesis, we found that CORM-2 treatment during AP significantly inhibited macrophage TNF-α production in the pancreas as well as in distant tissue, such as the spleen.

High levels of TNF-α in mouse models and patients with AP are associated with severe disease (26, 27). TNF-α activation triggers generation of TNF-α as well as other proinflammatory cytokines and chemokines relevant to the pathogenesis of AP. Levels of endotoxins such as LPS and TLR4 ligand correlate with systemic complications, mortality, and disease severity in patients with AP (28). Patients with severe and complicated AP have elevated endotoxin levels in
blood and peritoneal fluid (29). However, the initial injury and early complications associated with AP are likely related to sterile inflammatory process or endogenous ligand-mediated TLR activation, not to endotoxins (30). More recently, substances released by stressed or damaged cells, such as HMGB1, S100A8/9, and HSPs, have been shown to trigger TLR4 signaling, generate proinflammatory cytokines, and mediate necrosis-induced sterile inflammation (13, 31). Pancreatic acinar cell necrosis is an early event in AP, and serum HMGB1 levels are significantly elevated in patients with AP. Furthermore, high HMGB1 serum levels correlate with worsening clinical course and mortality (32). Similar results have been observed in preclinical animal models of AP (33). Using both human and mouse monocytes/macrophages, we showed here that CORM-2 inhibited both endogenous (HMGB1 and S100A8) and exogenous (LPS) ligand-mediated TLR4 activation, supporting a potential therapeutic role for CORM-2 in both early and late stages of human AP.

TLR4 and MD2 form a heterodimer to recognize LPS, and the physical interaction between TLR4 and MD2 is essential for TLR4 maturation and binding efficiency to its ligands (16). Nakahira et al. showed that CO inhibits TLR signaling by regulating reactive oxygen species–induced trafficking of TLRs to lipid rafts (34). Moreover, Rocuts et al. used the βTC3 cell line to show that CO inhibits the physical interaction between TLR4 and MD2 and also blocks TLR4 glycosylation, a necessary step for TLR4 trafficking to the cell membrane (17). Based on these studies, we hypothesized that CORM-2 treats AP by inhibiting TLR4 receptor complex formation, thereby interfering with TLR4 activation. Using in vivo and in vitro studies and mAbs that recognize the TLR4/MD2 complex versus total TLR4, we found that CORM-2 suppressed TLR4/MD2 complex expression. This also translated to lower TLR4 ligand binding, as shown by our FITC-LPS studies using a mouse macrophage cell line and freshly isolated primary/peritoneal macrophages. High-resolution crystal structure of murine TLR4/MD2 complex revealed several molecular recognition sites on the TLR4/MD2 interface that could serve as potential targets for blocking the TLR4 signaling pathway (35). Future studies will need to address the exact mechanism by which CO disrupts the association of TLR4 and MD2.

**Figure 5**

CORM-2 decreases LPS binding to TLR4/MD2 receptor complex. (A) Flow cytometry showing binding of FITC-LPS to RAW264.7 cells treated with VE or CORM-2. FITC-LPS–untreated cells (blank) are shown as a control. Relative FITC-LPS binding to RAW264.7 cells was quantified. Cell lysates were collected for TLR4 and MyD88 protein determination by Western blot. (B) RAW264.7 cells were pretreated with VE or CORM-2 for 30 minutes, then incubated with FITC-LPS. Cells were then washed and fixed for analysis by fluorescence microscopy. Green, FITC-LPS; blue, DAPI (nuclear stain). Original magnification, ×600. (C) Peritoneal macrophages from WT and TLR4 KO mice were isolated and treated with VE, CORM-2, or iCORM-2 for 4 hours, then analyzed by flow cytometry. Macrophages were gated (Lin–CD11b–CD11c–F4/80+) and analyzed for TLR4/MD2 expression and FITC-LPS binding. Shown is a representative FACS plot from at least 3 independent experiments. Data are mean ± SEM. *P < 0.05.
The pathogenesis of AP. Chimeric TLR4 KO→WT mice had less severe AP; moreover, in the absence of leukocyte TLR4 expression, CORM-2 did not offer additional protection. These results, together with the observed inhibitory effects of CORM-2 on monocyte/macrophage TNF-α expression, suggest that the therapeutic effects of CORM-2 in AP are likely mediated by disruption of monocyte/macrophage TLR4 activation.

In addition to CO release, CORM-2 has other effects, including inhibition of potassium channel (Kv2.1), activation of nonselective cation current, and production of reactive oxygen species (36–38). Although it is hard to rule out these effects in our model, we did not see improvement or worsening of AP using iCORM-2 and RuCl₃, which are depleted of and incapable of releasing CO, respectively. Even though we did not test the effect of inactive CORM-2 forms on freshly isolated acinar cells, with the exception of slightly higher calcium influx, we did not see significant acute effects of CORM-2 based on amylase secretion or NF-κB activation. It is possible that prolonged and/or repeated exposure may have an effect; alternatively, the CO may have circumvented the effects of the ruthenium complex.

Despite the beneficial and antiinflammatory effects of CO in various diseases and injury models, there has been little progress with respect to its translation and use in clinical settings. Low-dose inhalational CO has been shown to have antiinflammatory
The Journal of Clinical Investigation

http://www.jci.org   Volume 124   Number 1   January 2014

pretreated cells are able to ameliorate AP once adoptively transferred. Moreover, the pretreated cells did not transfer any inactive or active CORM-2. This finding is highly notable, and the therapeutic approach is likely to have utility in other diseases in which CO or active CO-RMs have been shown to be effective. Our findings support the potential use of ex vivo CORM-2–primed monocytes (which can be obtained easily from patients’ blood) in a clinical setting, thereby avoiding the feared systemic toxicities associated with CO therapy.

In summary, we demonstrated here that CORM-2 inhibits monocyte/macrophage TLR4/MD2 receptor complex activation and has a therapeutic role in treating mouse models of AP. Using mouse and human monocytes/macrophages, we showed that CORM-2 inhibited both endogenous and exogenous ligand-dependent TLR4 activation and TNF-α generation. Thus, CORM-2 is likely to be effective in the early stages of AP, in which sterile inflammation and necrosis are key, as well as in the later and severe stages of AP, in which bacterial translocation and endotoxin-mediated inflammatory events play a critical role.

**Figure 7**
CORM-2–primed cells ameliorate experimental AP. (A) Mice were injected hourly with caerulein a total of 7 times, treated with CORM-2– or VE-primed CD11b+ monocytes/macrophages 90 minutes after the first caerulein injection, and euthanized 12 hours after the first caerulein injection. (B and C) Pancreatic tissues were collected for H&E staining (B) and histology scoring (C). Scale bar: 100 μm. (D) Serum lipase measurements. (E) Pancreatic trypsin activity. (F) Pancreatic p-IκBα, p-P65, and P65 protein expression, determined by Western blot. (G) RNA from VE- and CORM-2–primed monocytes/macrophages was isolated for quantitative PCR analysis. Results are shown as fold change relative to VE (assigned as 1; dashed line). Data are mean ± SEM of at least 3 independent experiments.

effects against ventilatory-induced lung injury, a common hurdle in intensive care units, and was associated with decreased TNF-α (39). The toxicity of CO has long been known, and experts in CO-related toxicity are concerned about even modest doses of therapeutic CO (40). Active or inactive CO-RMs, at the concentrations used in our present studies, have previously been shown not to be toxic to mammalian cells in vitro and to rats in vivo (7, 41). However, Winburn et al. reported in vitro cytotoxic effects associated with ruthenium-based CO-RM byproducts, but not with CO, and suggested that accumulation of ruthenium in vivo might limit clinical application of these compounds (42). With these concerns in mind, we tested whether CORM-2–activated cells have the ability to transfer protection and treat experimental AP. Our data showed that CORM-2–activated monocytes/macrophages have a beneficial role in experimental AP. CORM-2–activated monocytes/macrophages upregulated the genes encoding the antiinflammatory cytokines IL-10 and IL-22, which were previously shown to be protective in experimental AP (22, 43). These cytokines may contribute to a mechanism whereby CORM-2–pretreated cells are able to ameliorate AP once adoptively transferred. Moreover, the pretreated cells did not transfer any inactive or active CORM-2. This finding is highly notable, and the therapeutic approach is likely to have utility in other diseases in which CO or active CO-RMs have been shown to be effective. Our findings support the potential use of ex vivo CORM-2–primed monocytes (which can be obtained easily from patients’ blood) in a clinical setting, thereby avoiding the feared systemic toxicities associated with CO therapy.
Furthermore, our data demonstrated that ex vivo CORM-2–primed monocytes/macrophages have the ability to transfer protection and treat experimental AP. Such a cellular therapeutic approach not only offers an alternative treatment route, but also avoids the toxicities associated with systemic administration of ruthenium and CO-based therapies.

**Methods**

**Mice.** Mice (including Balb/c, C57Bl/6, and TLR4 KO mice) were purchased from Jackson Laboratory and housed under pathogen-free conditions.

**AP models.** For caerulein-induced pancreatitis, age- and sex-matched mice were fasted for 12–16 hours with free access to water. Mice then received 7 hourly i.p. injections of saline as control or 50 μg/kg caerulein (Sigma-Aldrich) and were followed up to 12 hours. For the CDE model of pancreatitis, young female mice (16–20 g) were fasted, then fed with choline-deficient diet (Harlan Teklad) supplemented with 0.5% DL-ethionine (Sigma-Aldrich) or normal chow as control (22).

**CORM-2 treatment.** CORM-2 dosing was based on past dose titration studies and reported effectiveness of a single systemic 8-μg/kg dose in rodents (44–46). CORM-2 (8 mg/kg i.v.; Sigma-Aldrich) was administered to mice at the indicated times. iCORM-2 was generated as described previously by addition to cell culture medium overnight (18 hours) at 37°C and used to prime monocytes/macrophages. For intracellular TNF-α staining, immediately after isolation, cells were cultured in RPMI and stimulated with VE, 10–100 ng/ml LPS (Invivogen), 100 ng/ml mouse S100A8 (ProSpec), or 100 ng/ml human HMGB1 (ProSpec) for 4 hours in the presence of 10 μg/ml brefeldin A (BFA; eBioscience). Cells were washed, stained with surface markers, and then fixed and permeabilized using a kit (eBioscience) according to the manufacturer’s guidelines. Mouse PE-conjugated TNF-α or isotype control PE-conjugated IgG1 (BD Biosciences) was used for intracellular staining. Dead cells were excluded from analysis using violet viability stain (Invitrogen). Cells were acquired on a LSRII or Fortessa (BD Biosciences) and analyzed with FlowJo software (Treestar Inc).

**Generation of BM chimeric mice.** BM cells were collected from WT or TLR4 KO mice by flushing femur and tibia as above with HBSS containing 2% bovine calf serum (BCS). Chimeric mice were generated by transferring donor WT or TLR4 KO BM cells into irradiated WT recipient mice (n = 10 per group). Recipient mice were lethally irradiated with a signal dose of 9.5 Gy, after which 5 × 10⁶ BM cells/mouse were transferred via retro-orbital injection. The resulting WT→WT and TLR4 KO→WT mice were allowed to recover for at least 8 weeks to ensure stable engraftment before being subjected to AP induction.

**CORM-2–primed cell transfer.** BM cells were isolated from Balb/c mice as above, and CD11b+ cells were enriched with CD11b microbeads (Miltenyi Biotec). The CD11b-enriched cells were treated with either VE or 100 μM CORM-2 overnight. After washing with PBS, 5 × 10⁶ cells were transferred i.v. into mice undergoing caerulein-induced pancreatitis, 90 minutes after the first caerulein injection.

**Western blot and quantitative PCR assay.** Mouse pancreatic or cells were homogenized in RIPA buffer containing protease inhibitors, and iBeSt, phospho-iBeSt, P65, and phospho-P65 antibodies (Cell Signaling) were used for Western blot. CORM-2–primed cells were lysed with TRIzol for RNA extraction. cDNAs were generated using GoScript reverse transcription system (Promega). Quantitative PCR was performed with ABI-7900 sequence detection system (Applied Biosystems) using the following specific TaqMan probes and primers: Il22 forward, 5′-GACAGGTTCAGCCCTACAT-3′; Il22 reverse, 5′-CTGGATTTCTGGTCCTAC-3′; Il22 probe, 5′-CAG-GAAAGGCCACCTCCTGC-3′; Il10 forward, 5′-CCCGAATCTAAGGAGCAATTTTATGATAT-3′; Il10 reverse, 5′-TCACTTTCACTGCTCAC-3′; Il10 probe, 5′-TGAGTCAACGGCCCTCAAGCC-3′; Tnfα forward, 5′-CCAAGGGAATTAGGAGGAGG-3′; Tnfα reverse, 5′-CTCCACTTGTTGTTGCTA-3′; Tnfα probe, 5′-TGGCCCCAGACCTTACACTA-3′. Samples were normalized to Gapdh and displayed as fold change relative to control.

**Ca²⁺ influx assay.** Freshly isolated pancreatic acinar cells were treated with VE or CORM-2 for 1 hour, loaded with 2 μM Fura 2-AM (MP Biomedicals) for 30 minutes at 37°C, and then washed extensively. Prior to Ca²⁺ influx measurements, 100 nM caerulein was added. Ca²⁺ influx was quantified using a dual-excitation spectrofluorometer as described previously (51, 52). Excitation at 340 and 380 nm and emission at 510 nm were measured, and results are expressed as fluorescence ratios.

**CO and ruthenium determination.** Release of CO from medium or cells was assessed by measuring the conversion of deoxymyoglobin (deoxy-Mb) to carbonmonoxo-myoglobin (MbCO). The amount of MbCO formed was quantified by measuring absorbance at 540 nm as described...
previously (7). In brief, myoglobin solution (final concentration, 66 μM; Sigma-Aldrich) was prepared fresh by dissolving the protein in 0.04M-phosphate buffer (pH 6.8). Sodium dithionite (0.1%) was added to convert myoglobin to deoxy-Mb prior to each reading. For standard curves, different concentrations of CORM-2 were directly added to the myoglobin solution. The presence of CORM-2 was determined by ICP-MS at the School of Earth Sciences Environmental Measurement Center of Stanford University.

Statistics. Unpaired Student’s t test was used to determine statistical significance. A P value less than 0.05 was considered significant. Values are expressed as mean ± SEM (Prism 4; GraphPad Software). Unless otherwise indicated, results are from at least 3 independent experiments.

Study approval. All animal experiments were approved by Stanford University institutional animal care and use committees.

Acknowledgments
We thank Yi Wei and Yuehe Tang for technical assistance. This work was supported by a Robert Wood Johnson Foundation grant to (A. Habtezion), NIH grant DK092421 (to A. Habtezion), and Digestive Diseases Center grant DK56339 (to Stanford University).

Received for publication May 31, 2013, and accepted in revised form October 11, 2013.

Address correspondence to: Aida Habtezion, Stanford University School of Medicine, Department of Medicine, Division of Gastroenterology and Hepatology, 300 Pasteur Drive, Stanford, California 94305, USA. Phone: 650.725.3362; Fax: 650.723.5488; E-mail: aidah@stanford.edu.