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Class B Scavenger Receptor Types I and II and CD36 Targeting Improves Sepsis Survival and Acute Outcomes in Mice

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Class B scavenger receptors (SR-Bs), such as SR-BI/II or CD36, bind lipoproteins but also mediate bacterial recognition and phagocytosis. In evaluating whether blocking receptors can prevent intracellular bacterial proliferation, phagocyte cytotoxicity, and proinflammatory signaling in bacterial infection/sepsis, we found that SR-BI/II– or CD36-deficient phagocytes are characterized by a reduced intracellular bacterial survival and a lower cytokine response and were protected from bacterial cytotoxicity and inflammation, including hypotension, intravascular coagulation, and endothelial dysfunction, which eventually lead to multiorgan failure and death. Despite considerable patient care advances in intensive care units, the mortality from sepsis is still increasing in critically ill patients (1–3). 

Sepsis is a combination of clinical syndromes and pathologic processes, including septic shock, disseminated intravascular coagulation, and endothelial barrier dysfunction, followed by multiorgan failure resulting from generalized infection. Sepsis, particularly bacterial, develops when a critical mass of bacteria overcomes local containment and enters the general circulation, leading to bacteremia and triggering excessive systemic inflammation, hypotension, intravascular coagulation, and endothelial dysfunction, which eventually leads to multiorgan failure and death. Despite considerable patient care advances in intensive care units, the mortality from sepsis is still increasing in critically ill patients (1–3). An incomplete understanding of sepsis pathophysiology has slowed the development of effective treatments that are needed to reduce the intractably high mortality (4). Several strategies for treating human sepsis, based on the targeting of various systemic proinflammatory mediators or systemic coagulation, have failed in large multicenter clinical trials (5–7). Because the current sepsis-treatment approaches remain limited to a combination of antibiotic intervention and supportive therapy, novel strategies are needed to improve sepsis therapeutics and outcomes.

Bacterial infection begins with limited local bacterial proliferation, followed by a local inflammatory response and rapid granulocyte recruitment to the infected site (8–10). These initial events are critically dependent on pattern recognition receptors that mediate bacterial binding and downstream intracellular signaling in responsive cells, resulting in the secretion of cytokines and chemokines (10, 11). Highly expressed TLR, nucleotide-binding domain-like receptor, and RIG receptors on phagocytic cells make them primary sensors of infection and inflammation (11, 12). In contrast to TLRs, which mediate only bacteria-induced signaling leading to cytokine production, scavenger receptors play a dual role that includes both pathogen-induced signaling, followed by cytokine secretion, and bacterial phagocytosis/clearance (13–16). Recent data describe a critical role for CD36 and SR-BI/II, class B scavenger receptors (SR-Bs) that are also known as lipoprotein receptors (17–21). CD36 mediates bacterial adhesion, internalization, and lysosomal sequestration.

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Abbreviations used in this article: AHP, amphipathic helical peptide; AKI, acute kidney injury; ALT, alanine transaminase; AST, aspartate transaminase; BMC, bone marrow cell; BUN, blood urea nitrogen; CLP, cecal ligation and puncture; GC, glucocorticoid; KO, knockout; LDH, lactate dehydrogenase; MC, mineralocorticoid; NHI, National Institutes of Health; PMN, polymorphonuclear leukocyte; Scr, serum creatinine; SR-B, class B scavenger receptor; WT, wild-type.

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Lysosomal sequestration of Gram-positive bacteria in CD36-expressing cells facilitates lysosomal-integrated TLR2-dependent signaling and cross-talk (22). CD36 was also reported to mediate a direct activation of Fyn/Lyn small GTP-binding proteins, followed by the downstream activation of JNK, p38, and ERK1/2 kinases, independent of TLR signaling (17, 23–25). Similarly, we and other investigators demonstrated that SR-BI/II receptors mediate bacterial phagocytosis (21) and bacterium-induced secretion of cytokines (18, 23). Bacterial interaction with SR-BI/II can also lead to incomplete phagocytosis, during which bacteria escape from the lysosomal compartment to cytosol. Lysosomal escape/incomplete phagocytosis protect bacteria from phagocytic destruction, as well as shield them from systemic antibiotics; hence, bacteria can proliferate (21). Our findings suggest that SR-B family receptors might accelerate sepsis because they promote inflammation and mediate incomplete phagocytosis. Evasion from systemic antibiotics due to cytosolic escape can allow unimpeded intracellular bacterial expansion and could facilitate granulocyte cytotoxicity (17, 21), as well as systemic dissemination of bacteria. Therefore, genetic or pharmacological inhibition of SR-B receptors might enhance containment of the local infection and reduce systemic inflammation.

We have proposed that the absence of SR-B receptors or targeting of SR-B receptors using receptor ligands/antagonists can reduce downstream events following interactions between receptor(s) and entities recognized by SR-B, such as pathogens, their cell components, or other proinflammatory factors/inflammagens, including acute-phase and heat-shock proteins (17, 18, 23). We and other investigators recently established that L-37pA, an amphipathic helical synthetic peptide, is a ligand for SR-BI/II (18, 26) and CD36 (17, 23) and a potent receptor antagonist (17). L-37pA blocks phagocytosis of bacteria and bacterium-induced cytokine secretion mediated by both SR-BI (18, 21) and human CD36 (17, 23). Because L-37pA also reduces bacterium-stimulated immune cell activation, it could be beneficial by limiting bacterial proliferation and systemic inflammation and reducing tissue damage in sepsis. In this study, we analyzed the potential benefits of targeting SR-BI/II and CD36 in a mouse model of peritoneal sepsis induced by cecal ligation and puncture (CLP). The CLP model, especially when adequate antibiotic treatment and fluid resuscitation are used, replicates many of the hallmarks of severe septic shock, such as polymicrobial bacteremia, hypotension, and multiple organ failure, including acute kidney injury (AKI) (27). We studied the effects of the absence (SR-BI/II- or CD36 knockout [KO] mice) and blockade (with L-37pA) of these receptors on sepsis survival, multiple organ damage, and inflammation. Our data indicate that SR-B absence or blockade increases animal survival by increasing local peritoneal granulocyte infiltration and limiting bacterial proliferation, therefore reducing tissue toxicity and systemic inflammation.

Materials and Methods

Animals

The National Institutes of Health (NIH) criteria for laboratory animal care were used in this study. CD36 KO mice (C57BL/6 background) were kindly provided by Dr. Kathryn Moore’s laboratory and grown in a colony at an NIH animal facility. SR-BI/II mice (C57BL/6 background) were obtained from Jackson Laboratories, and a colony was established at NIH. To ensure the development of sepsis-induced AKI in the C57BL/6 background (27, 28), age-matched C57BL/6 mice (24–30 wk old) were used as controls for KO mouse studies. For pharmacological studies, CD-1 mice (6–8 wk old; NCIDCT) were used because they develop sepsis-AKI at a younger age (29).

Surgery

The CLP procedure was described in detail previously (27, 28, 30–33). Briefly, the cecum, at 12 mm in length, was ligated, punctured through with a 21-gauge needle, gently squeezed to express 1 mm of fecal material, and then returned to the central abdominal cavity. In sham-operated animals, the cecum was just identified and replaced in the peritoneal cavity. Immediately after surgery, prewarmed normal saline (30 ml/kg) was given i.p., and s.c. antibiotics were administered (imipenem/cilastatin, 14 mg/kg in 1 ml/30 g mouse of normal saline at 6 h and 7 mg/kg in 1 ml/30 g mouse of 2/3 [100 mM NaCl] normal saline at 18 h). Blood was collected by cardiac puncture for measurement of serum markers of organ injury and cytokine responses at 24 h after surgery. Kidneys were fixed in 10% neutral buffered formalin for histology.

L-37pA intervention study

The amphipathic helical synthetic peptide (18, 26) L-37pA (an SR-B receptor antagonist) or L3D-37pA (a nonhelical peptide with the same sequence but having three L-to-D substitutions) was injected i.v. at a dose of 10 mg/kg in 0.3 ml PBS. PBS was used as another control. The intervention was repeated 6 h after surgery. To explore the dosing window for these peptides, 10 and 50 mg/kg L-37pA was injected at 0 and 6 h after CLP, respectively.

Survival study

The animals were observed for survival every 6–12 h after surgery. Subcutaneous antibiotics and fluid (imipenem/cilastatin, 14 mg/kg in 1 ml normal saline) were administered at 6 h after surgery and repeated (imipenem/cilastatin, 7 mg/kg in 1 ml normal saline) every 12 h for 4 d. There is a substantial glucocorticoid (GC) and mineralocorticoid (MC) deficiency in SR-BI/II KO mice (34); therefore, the animals received 2 × 10^-3 M dexamethasone (for GC replacement) and 2 × 10^-5 M fludrocortisone acetate (for MC replacement) in drinking water, starting at 24 h before surgery, for the duration of the experiment. One set of control mice also received the same hormone-containing drinking water. Animals with extreme morbidity were euthanized.

Renal pathology

Tissue was fixed in 10% formalin and embedded in paraffin; 4-μm sections were cut and then stained with periodic acid-Schiff reagent. Renal tubular damage was defined as tubular epithelial swelling, loss of brush border, and peritubular vacuolization. The degree of kidney damage was estimated, as previously described (30).

Blood chemistry and cytokine measurement

Blood urea nitrogen (BUN), aspartate transaminase (AST), and alanine transaminase (ALT) were measured using an automatic analyzer (Hitachi 917; Boehringer Mannheim, Indianapolis, IN). Serum creatinine (Scr) was measured by HPLC, as previously described (35). Serum TNF-α, IL-6, and IL-10 were determined by ELISA (R&D Systems, Minneapolis, MN).

Peritoneal cell and bacteria-proliferation analyses

Mice were anesthetized at 18 h for blood drawing and organ collection. Immediately after blood collection, peritoneal lavage was performed with 5 ml sterile PBS using an 18-gauge needle (9). The lavage fluid was collected in sterile tubes and placed on ice. Peritoneal cells were counted and, after centrifugation, spun and resuspended in RPMI 1640 containing 10% FBS. Peritoneal cells were counted and, after centrifugation, spun and resuspended in RPMI 1640 containing 10% FBS. Peritoneal cell and bacteria-proliferation analyses

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Cell culture

HEK 293 and HeLa cells were stably transfected to express human SR-BI, SR-BII, or CD36 (20, 23). The cells were plated in cell culture-treated plates (Costar) and cultured in DMEM containing 10% FBS and penicillin/streptomycin.

Bone marrow cells (BMCs) were isolated from normal, SR-BI/II, and CD36 KO mice (17, 21). To produce granulocytic cells, isolated BMCs were plated on various culture-treatment plates for real-time and dynamic monitoring of cell proliferation and viability of adherent cells (ACEA instrument) in 16-well plates (ACEA Biosciences, San Diego, CA) or 8-well immunocytochemistry slide chambers in RPMI 1640 containing 10% FBS and 10 ng/ml mouse GM-CSF and cultured for 5 d. About 90–95% of plate-adherent bone marrow-derived cells were GR-1+, as revealed by anti-Gr-1 immunostaining (data not shown).

TARGETING CLASS B SCAVENGER RECEPTORS IN SEPSIS
Fluorescently labeled bacteria and lysosomes

Live *Escherichia coli* and *Staphylococcus aureus* were labeled with Alexa Fluor 488, using a protein labeling kit (Invitrogen), following the vendor’s instructions. All bacterial uptake and phagocytosis studies were performed using DMEM containing 2 mg/ml BSA without antibiotics. HeLa cells were incubated with bacteria at ∼50 labeled bacteria/cultured cell. Culture plates were briefly centrifuged to accelerate bacterial sedimentation, and the cells were incubated at 37°C for 1 h. After three washings with PBS to remove unattached bacteria, slides were incubated with fluorescent LysoTracker Red. After a 30-min incubation with trackers, slides were washed with PBS, fixed with 4% paraformaldehyde, and sealed or viewed immediately without fixation. Visualization was achieved using Alexa Fluor 488/594-labeled anti-mouse/rabbit IgG secondary Abs (Invitrogen). To assess subcellular localization, images were obtained with a Zeiss 510 laser scanning confocal microscope, using a krypton-argon Omnichrome laser with excitation wavelengths of 488 and 568 nm for Alexa 488 and Alexa 568 labels, respectively.

Antibiotic-protection assay

Cultured cells were incubated in DMEM containing 10% FCS, 100 μg/ml penicillin/streptomycin, and K12 *E. coli* (∼10 bacteria/cell) in culture wells. After a 1-h incubation at 37°C, plates were washed with PBS and lysed in H2O for 20 min on ice. Lysates were plated on blood agar dishes at various dilutions and incubated overnight at 37°C.

Granulocyte cytotoxicity/cytokine-response assays

Cells were aliquoted into ACEA 16-well plates and allowed to sediment at room temperature for 30 min. The plates were then inserted into analyzing slots of the ACEA instrument (ACEA Biosciences). Cells were cultured for 24–96 h until reaching confluency (various genetically modified HEK 293 cells) or differentiating into granulocytic cells (BMcs isolated from various mice). K12 *E. coli* were added at a concentration of ∼10 bacteria/cell. Cell layer resistance was analyzed for the next 48–72 h. To establish the role of CD36 and SR-BI/II in pathogen/pathogen-associated product-induced inflammation, various cells were incubated with bacteria, LPS, or GroEL, for 24 h, followed by media harvesting. Conditioned media were used to measure IL-6 and IL-8 in mouse and human cells, respectively.

Statistical analyses

All data are expressed as mean ± SE. ANOVA with a multiple comparison correction or t test (Sigma-Stat program; Systat Software, Point Richmond, CA) was used for detecting differences between groups. A p value < 0.05 was accepted as statistically significant.

Results

**SR-BI/II and CD36 are important for bacterial phagocytosis, cytosolic invasion, granulocyte survival, and cytokine secretion in vitro**

SR-BI/II (CLA-1/2) and CD36 are important parts of the host-defense system, mediating bacterial recognition through bacterial binding and internalization and bacteria-induced inflammation (17, 21, 22, 36). Bacterial internalization is associated with both bacterial lysosomal sequestration (phagocytosis) and lysosomal escape (incomplete phagocytosis). Given that bacterial phagocytosis is important for bacterial killing and clearance, lysosomal escape can lead to cytosolic invasion, unchecked bacterial proliferation, and cytotoxicity. To analyze the potential impact of class B scavenger receptors on bacterial phagocytosis and lysosomal escape, we first assessed uptake and colocalization of fluorescently labeled bacteria (green signal) with a specific lysosomal marker, LysoTracker Red (red signal) in HeLa cells stably transfected with human SR-BI (CLA-1), SR-BII (CLA-2), or human CD36. As seen in Fig. 1, CLA-1, CLA-2, or CD36 expression greatly increases bacterial uptake compared with HeLa cells stably transfected with empty vector (Mock). Both *E. coli* and *S. aureus* were substantially internalized into lysosomes (yellow signal/colocalization). At the same time, a number of bacteria remained outside of the lysosomal compartment, which may reflect lysosomal escape and cytosolic proliferation.

To assess the role of extralysosomal bacterial sequestration in bacterial proliferation and cytotoxicity, we analyzed intracellular bacterial counts in HeLa cells and granulocytes infected either with K12 *E. coli* or *S. aureus* in the presence of antibiotics (antibiotic-protection assay). Importantly, when bacteria were incubated with HeLa cells overexpressing scavenger receptors (CLA-1, CLA-2, or CD36) or BMC-derived granulocytes in the presence of antibiotics, the number of surviving bacteria was solely dependent on the rate of bacteria internalization and, consequently, intracellular escape from antibiotic killing and lysosomal degradation (21). In HeLa cells, the number of intracellular bacteria was greatly in-

![FIGURE 1](http://www.jimmunol.org/)

**FIGURE 1.** Role of scavenger receptor class B proteins in bacterial uptake and phagocytosis. HeLa cells transfected with empty vector (Mock), CLA-1, CLA-2, or CD36 were incubated with Alexa Fluor 488-labeled K12 *E. coli* (upper panels) or with *S. aureus* (lower panels) for 1 h in DMEM containing 10% FCS, washed, and incubated in bacteria-free media in the presence of LysoTracker Red for 30 min. Live cultures were viewed using confocal microscopy to analyze phagocytosis of bacteria. Colocalization of Alexa Fluor 488-*E. coli* (green) and LysoTracker Red (red) is seen as yellow. The blue color shows DAPI-stained nuclei. Examples of the most intense colocalization are within white circles. Scale bar, 10 μm.
increased in SR-BI–, SR-BI/II–, or CD36-transfected HeLa cells (Fig. 2A). Granulocytes deficient in SR-BI/II and CD36 had 50 and 80% reductions in E. coli bacterial counts, respectively (Fig. 2B). When Gram-positive bacteria were used, they preferentially required CD36, because CD36 KO granulocytes had 90% reduced bacterial survival (Fig. 2B). Because SR-B deficiency reduced the ability of bacteria to invade BMC-derived granulocytes, whereas receptor overexpression increased, we analyzed whether the presence/absence of these receptors affects the survival of cells incubated with bacteria in the presence of antibiotics. As seen in Fig. 2C, HEK cells stably transfected to express human SR-BI, SR-BI/II, or CD36 rapidly deteriorated compared with mock-transfected HEK cells, which have low endogenous levels of these three receptors. In complementary experiments, scavenger class B receptor KO granulocytes demonstrated improved viability after bacterial challenge, surviving 8 and 14 h longer with SR-BI/II– and CD36-deficient cells, respectively (Fig. 2D). These data indicate that SR-B deficiency could potentially be beneficial in preventing sepsis and bacterial proliferation, but only in the presence of antibiotics, as the result of reduced incomplete phagocytosis, lysosomal escape, antibiotic evasion, and, as a consequence, decreased bacterial cytotoxicity.

Another important function of bacterial recognition by SR-B is the receptor-mediated inflammatory response. Indeed, an essential hallmark of severe sepsis is the development of septic shock due to overwhelming systemic inflammation, for which intervention could be beneficial. When we compared wild-type (WT) HEK 293 cells with HEK cells stably transfected with CLA-1 (SR-BI), CLA-2 (SR-BI/II), or CD36 scavenger receptors, peritoneal bacteria increased IL-8 secretion to varying degrees: CD36 > SR-BI > SR-BI/II > mock (Fig. 2E). BMC-derived granulocytes from SR-BI/II– and CD36-deficient mice produced 40 and 70% less IL-6, respectively (Fig. 2F). Receptors were overexpressed at relatively similar levels in HeLa cells; however, in bone marrow-differentiated macrophages/granulocytes, CD36 is expressed at higher levels than are SR-BI and SR-BII (data not shown). This is consistent with our observations that the intracellular bacterial count (survival) was <30% in CD36 KO versus ~70–100% in SR-BI/II KO macrophages/granulocytes. These data indicate that SR-B deficiency could be beneficial during severe infections as a result of reduced proinflammatory activation of phagocytes, as well as lower intracellular bacterial survival in the presence of antibiotics.

SR-BI/II and CD36 are critically important in CLP sepsis

Despite reduced proinflammatory activation of phagocytes, the effect of SR-B receptor family deficiency in vivo was surprisingly opposite to what was expected. Without antibiotic treatment, i.v. bacterial inoculation of CD36-deficient mice revealed reduced Gram-positive bacterial clearance, resulting in severe bacteremia during the first several hours (36). CLP-induced sepsis was also more severe in SR-BI/II–deficient mice than in normal mice (37–40).

These data point to an important role for these receptors in bacterial phagocytosis, which is clearly deficient in SR-BI/II and CD36 KO mice. To assess the role of SR-B receptors in sepsis and the potential for pharmacological intervention, we used antibiotic treatment as a part of the CLP model as well, to compensate for phagocytic deficiency in these mice. SR-BI/II KO mice are also characterized by defective lipoprotein metabolism causing adrenal insufficiency and impaired production of both adrenal steroid hormones (37–40). Corticosterone replacement was only partially effective at improving survival and reducing inflammation in SR-BI/II KO mice challenged with LPS or stressed by starvation (37, 40). Moreover, corticosterone replacement alone was insufficient to improve the survival of SR-BI/II KO mice with CLP-induced sepsis (38). We also found that aldosterone elevation, in response to CLP, LPS, or bacterial chaperonin 60, was also reduced in SR-BI/II KO mice (34). Because fluid and antibiotic treatments represent first-line interventions in septic patients (6, 7), we reanalyzed the role of SR-BI/II and CD36 deficiency in the development of CLP-induced sepsis using fluid and antibacterial treatment in both SR-BI/II and CD36 KO mice, with simultaneous correction of adrenal deficiency in SR-BI/II KO mice with combined GC and MC replacement. The relative adrenal deficiency of SR-BI/II KO mice may mimic the situation with some older human septic patients who have compromised adrenal cholesterol reserve. Because CD36 KO mice have only minor impairment of platelet activation (41), but normal adrenal function, these mice were not treated with GC/MC.

Granulocyte migration to the peritoneal cavity is an important host-defense mechanism during infectious peritonitis. Higher peritoneal phagocyte counts are associated with reduced peritoneal bacterial accumulation and positively correlated with survival rate in mice with CLP-induced sepsis. Because cultured SR-B KO granulocytes were protected from bacterial toxicity (Fig. 2D), we first analyzed peritoneal lavage in mice at 18 h after the CLP procedure. Compared with normal mice, the total number of

![FIGURE 2. Role of SR-BI/II and CD36 in bacterial uptake, bacterial cytoxicity, and pathogen-induced cytokine secretion. HeLa or HEK293 cells expressing CLA-1, CLA-2, or CD36 or empty plasmid or bone marrow-derived granulocytes isolated from control, SR-BI/II KO, and CD36 KO mice were incubated with various bacteria (K12 E. coli and S. aureus (A and B) or peritoneal polynuclear culture (C–F)) to analyze bacterial uptake using an antibiotic protection assay in HeLa cells (A), granulocytes (B); to analyze E. coli-induced cell death using the ACEA instrument in HEK cells (C) and granulocytes (D); and to analyze peritoneal bacteria-induced IL-8 secretion in HEK 293 cells (E) and granulocytes (F). For (E) (IL-8 secretion), mice were subjected to CLP, and peritoneal bacteria were isolated and expanded to provide a polybacterial culture, which was then added to transfected HEK 293 cells. After an 18-h incubation of bacteria with HEK 293 cells or granulocytes, media were harvested and used for IL-6 and IL-8 ELISA evaluations.](http://www.jimmunol.org/DownloadedFrom)
peritoneal cells increased 3-fold in both SR-BI/II and CD36 KO animals (Fig. 3A). Both KO mice strains had no statistically significant changes in peritoneal monocyte/macrophage cell counts (Fig. 3C), but they demonstrated greatly increased numbers of granulocytes/PMNs (Fig. 3B). The 4–6-fold increase (p < 0.05) in granulocyte/PMN accumulation was similar to data demonstrating neutrophil accumulation and improved bacterial containment in TLR9-deficient mice (10). Increased PMN accumulation inversely correlated with a drastic reduction in peritoneal bacteria in both SR-BI/II and CD36 KO mice relative to CLP-treated C57BL/6 control (Fig. 3D). Representative cytospin slides (Fig. 3E) show that 70–80% of peritoneal cells in SR-BI/II– and CD36-deficient mice after CLP are mostly granulocytes/PMNs, with a small number of monocyte/macrophage cells. Cytospin preparations of SR-BI/II and CD36 KO lavage cells had fewer intracellular and extracellular bacteria in peritoneal lavage samples (Fig. 3E, right panels). Without CLP, both WT and KO mice demonstrated a similar cellular composition of peritoneal cells (Fig. 3E, left panels).

These data demonstrate that SR-B–deficient granulocyte/PMN cells were protected in mice with CLP-induced sepsis that were treated with antibiotics. Because SR-B deficiency caused a 20–50-fold reduction in both intracellular and extracellular bacteria in peritoneal lavage, PMN protection likely resulted from reduced cellular toxicity and necrosis rather than attenuated apoptosis. The number of apoptotic cells was unchanged in peritoneal lavage cells from septic CD36 mice and was slightly increased in SR-BI/II KO mice (Supplemental Fig. 1); however, more definitive experiments are needed to eliminate the potential role of apoptosis. In agreement with earlier data (38), when animals were not treated with antibiotics, most SR-B KO animals did not survive 18 h postinfection. Surviving animals demonstrated a 2–3-fold higher peritoneal bacteria count compared with CLP septic controls (data not shown).

CLP development and progression were further analyzed by assessing systemic inflammation, organ damage, and animal survival. As seen in Figs. 4–6, sepsis in both SR-BI/II and CD36 KO mice was less severe than in control mice. SR-BI/II KO animals received dexamethasone (a synthetic GC) and fludrocortisone (a steroid hormone). In the absence of steroids, SR-BI/II KO mice did not survive 18 h after CLP (Fig. 6A) and steroid hormone-compensated SR-BI/II (Fig. 6B) mice (55 and 48%, respectively) compared with control C57BL/6 mice with (5%) or without (17%) steroid hormone. Because CD36 KO mice do not develop adrenal deficiency, neither they nor their C57BL/6 controls were treated with adrenal hormones. In the absence of steroids, SR-BI/II KO mice did not survive CLP sepsis (Fig. 6B). When we analyzed SR-BI/II/CD36 double-KO mice, we found that these mice do not survive without steroids; however, when GC/MC deficiency was compensated for by steroid supplementation, the double-KO mice had a survival rate similar to CD36 KO mice, although it was slightly attenuated.

L-37pA treatment increases peritoneal granulocyte accumulation and reduces bacterial proliferation in CLP septic mice

Amphiphatic helical peptides (AHPs) can reduce inflammatory activity in vitro (42), as well as systemic inflammation and lethality in endotoxin-induced septic shock in mice (43) and CLP-induced sepsis in rats (44). The effect of AHPs was suggested to be a result of LPS binding to AHPs, leading to LPS neutralization (42). We and other investigators also demonstrated that AHP, such as L-37pA, are strong antagonists/ligands for both CD36 and SR-BI/II (17, 18) and can block bacterial uptake and inflammatory activity in vitro (17, 18, 21). Because SR-B receptor deficiency was associated with reduced bacterial cytotoxicity, systemic inflammation, and decrease in mortality, we investigated whether L-37pA can improve peritoneal PMN cell survival, reduce peritoneal bacteria, and attenuate CLP-induced sepsis in mice (27, 29). To study these pharmacological effects of L-37pA, 6–8-wk-old CD-1 mice, which develop AKI due to CLP-induced sepsis at a much earlier time than do C57BL/6 mice, were used. Intravenous administration of L-37pA (10 mg/kg) immediately and 6 h after CLP surgery attenuated sepsis severity in 6–8-wk-old CD-1 mice. All mice were additionally treated with fluid and antibiotics to simulate the central strategy for treating critically ill septic patients.

**FIGURE 3.** Effect of SR-BI/II and CD36 deficiency on peritoneal fluid composition. Peritoneal lavage was collected to count the total number of peritoneal cells (A), granulocytes/PMNs (B), monocyte/macrophage cells (C), and bacteria (D) per mouse 24 h after CLP (n = 6–15). (E) Typical cytospin slides Giemsa stained for cell-composition analyses (original magnification ×400).
(4). As negative controls, mice received either PBS or the non-helical L3D-37pA peptide, which has three L-to-D amino acid substitutions (18) and does not bind to SR-BI/II and CD36.

Peritoneal lavage from PBS i.v.-injected septic mice at 18 h contained 7.6 ± 10^6 cells/mice, mostly PMNs and monocyte/macrophage cells with a number of internalized bacteria (Fig. 7A). Although the total number of cells was only slightly higher than the 5 × 10^6 cells seen in nonseptic (sham control) mice, there was a 10-fold increase in peritoneal granulocytes (Fig. 7B), similar to previously reported results (9, 10). In L-37pA-treated mice there was a further 2-fold increase in peritoneal cell count, which was predominantly associated with a 2.5-fold increase in granulocyte/PMN cell count, compared with PBS-treated mice (Fig. 7B). A number of monocyte/macrophage cells remained, similar to PBS-treated septic controls (Fig. 7C). Despite the absence of statistically significant overall changes in peritoneal bacteria in L-37pA–treated versus PBS-treated mice, ~25% of L-37pA–treated mice demonstrated a 95% reduction in bacteria in peritoneal fluids (Fig. 7D). These data indicate that L-37pA increased the number of granulocytes accumulating in the peritoneum, similar to the effect of SR-B deficiency seen in Fig. 3.

L-37pA inhibits systemic inflammation, reduces organ damage, and improves survival in murine CLP-induced sepsis

In L-37pA–treated mice, IL-6, IL-10, and TNF-α levels were significantly reduced (Fig. 8) compared with PBS and L3D-37pA–injected animals. Lower pro- and anti-inflammatory cytokine...
levels indicate improved control of infection in L-37pA–treated animals. The survival rate at 96 h after CLP increased 4-fold, from 6% in L3D-37pA– or PBS-treated mice to 27% in L-37pA–treated animals (Fig. 9A). A lower dose of L-37pA (10 mg/kg) did not affect plasma cholesterol and triacylglycerol levels, whereas a higher dose (50 mg/ml) led to hypertriglyceridemia and slight hypercholesterolemia (Fig. 9B, 9C). These effects of L-37pA are similar to the effects of D-4F peptide, which was also demonstrated to increase rat survival during sepsis by 2-fold (44). The increased animal survival with L-37pA treatment was associated with significantly reduced CLP-induced multiorgan damage (improved serum creatinine, BUN, AST, ALT, amylase, LDH) (Fig. 9D–I) and improved kidney histology (Fig. 9J, Supplemental Fig. 3). These data indicate that the final stages of sepsis, such as decreased organ function and increased organ damage, were significantly attenuated in mice treated with L-37pA.

Discussion

Modeling sepsis remains challenging in small experimental animals. Recent reviews indicate that CLP-induced sepsis best duplicates the septic peritonitis often seen in older human patients (45, 46). CLP mimics many features of human sepsis, including hemodynamic changes, activation of pro- and anti-inflammatory cytokines, systemic inflammation, disseminated intravascular coagulation, multiple organ failure, systemic immune-depression, and death. Also, very importantly, the use of outbred 6–9-wk-old mice facilitates the study of sepsis in a more reproducible manner. Here, we investigated the effects of a novel L-37pA peptide on survival and multiorgan damage after CLP-induced sepsis in outbred C57BL/6 mice.

FIGURE 6. Scavenger receptor deficiency reduces mortality from sepsis. (A) Survival analysis of age- and background-matched WT mice (n = 17) versus CD36 KO mice (n = 17). (B) Survival analysis of age- and background-matched WT mice (n = 7), WT mice with GC/MC supplementation (n = 10), SR-BI/II KO mice (n = 8), and SR-BI/II KO mice with GC/MC supplementation (n = 9). (C) Survival analysis of age- and background-matched WT mice (n = 7), WT mice with GC/MC supplementation (n = 10), CD36− SR-BI/II double-KO mice (n = 4), and CD36− SR-BI/II double-KO mice with GC/MC supplementation (n = 11).

FIGURE 7. Effect of L-37pA on peritoneal fluid composition. Peritoneal lavage was collected to count the number of total peritoneal cells (A), granulocytes/PMNs (B), monocyte/macrophage cells (C), and bacteria (D) in 7–15 animals undergoing CLP at 24 h.

FIGURE 8. L-37pA inhibits inflammatory cytokine response in murine sepsis model. Serum inflammation-associated cytokines TNF-α (A), IL-6 (B), and IL-10 (C) were tested at 24 h after surgery in sham group (n = 4), PBS control group (n = 6), L3D-37pA control peptide group (n = 7), and groups administered L-37pA (10 mg/kg and 50 mg/kg, L-37pA 10 and L37-pA 50, respectively) at 0 and 6 h after CLP (both n = 7). *p < 0.05, versus PBS control.
old CD-1 or older 4–6-mo-old C57BL/6 mice allows stably reproducible sepsis-induced AKI, which is commonly observed in human sepsis. The CLP model was used throughout our study to investigate the role of SR-BI/II and CD36 in C57BL/6 mice or the pharmacological effects of L37pA using much younger and much less expensive CD-1 mice.

Peritoneal granulocyte/PMN mobilization is a primary host-defense mechanism to prevent bacterial expansion and potential systemic bacterial dissemination (10, 47, 48). Increased or decreased granulocyte/PMN migration reversibly correlates with the rate of peritoneal bacterial proliferation and severity of CLP-induced sepsis (9, 10). Because both systemic inflammation and multiorgan damage were reduced in L-37pA-treated mice and SR-B–deficient animals, we hypothesize that the effects observed in this study could be due to improved peritoneal granulocyte survival and subsequent local bacterial containment. We suggest that SR-B family targeting, in combination with systemic antibiotic therapy, could be beneficial because of reduced cytotoxic bacterial proliferation and a subsequent decrease in peritoneal phagocyte damage and death (21).

These data also establish an important role for class B scavenger receptors in the development of local and systemic innate immune responses during severe infection (sepsis). In Fig. 10, we propose a model of sepsis that integrates the data from this study, as well as...
previous observations made by us and others, on SR-B receptor family-dependent endocytosis (17, 21, 35), bacterial lysosomal escape (21), indirect internalization-dependent TLR receptor cross-talk (22, 49), and direct pathogen-induced SR-B family-mediated cytokine production (17). According to this model, SR-B family receptors are both complementary and redundant to various bacterial receptors, such as the FcRs, scavenger receptors of various classes (13–16), and other pathogen-recognizing structures, such as TLR, nucleotide-binding domain-like receptor, and RIG (11, 12). Initial stages of bacterial recognition are mediated to a significant extent by TLR receptors. Upon interaction with surface TLR2/4 receptors, bacteria induce downstream activation of various nuclear transcription factors, which induce the production of various cytokines. TLR receptors do not mediate bacterial internalization; this function is mostly fulfilled by other receptors, including scavenger receptors of the class B family. After receptor-mediated bacterial engulfment and endocytosis, lysosomally degraded bacterial products can interact with endosomally/lysosomally seques- tered TLR7 and TLR9, thus amplifying TLR function. In contrast to the classical phagocytic FcRs, B cell scavenger receptors also mediate signaling in both a TLR-dependent and -independent manner. Thus, it was demonstrated that pathogen interaction with CD36 (17, 41, 50) directly induces INK-dependent signaling, leading to a direct stimulation of cytokine secretion in stably transfected HEK293 cells. Similarly, SR-BII-mediated bacterial- and LPS-inducible signaling can lead to cytokine production in SR-BI/II–expressing cells (34). Because of the redundancy among pathogen/pattern recognizing receptors, phagocytic cells deficient in a single receptor may demonstrate limited or no reduction in pathogen-associated downstream events, including endocytosis and nuclear transcriptional factor activation. In some cell types with a unique combination of expressed pattern recognizing receptors, the absence of one can even lead to increased pathogen recognition through other receptors and unexpectedly stronger proinflamma- tory signaling. For example, SR-BI/II–deficient macrophages had a modestly increased, relative to normal cells, cytokine production in response to LPS (38). We have also seen such effects for peritoneal macrophages but not for BMC-derived granulocytes, in which SR- BII and CD36 deficiency resulted in a 50–60% reduction of cyto- kinase secretion (Fig. 9). In addition to gene activation that can lead to cytokine production, pathogens induce downstream signaling to activate endoctic processes. After the initial bacterial binding/ adhesion, SR-B receptors mediate bacterial internalization/lyso- somal sequestration (21); however, SR-BI can lead to incomplete phagocytosis, allowing bacteria to escape from the lysosomes into the cytosol (21) where they can evade systemic antibiotics. In this pro- tected niche, bacteria can proliferate and activate intracellular TLRs and other pathogen receptors, with resultant gene activation and in- flammatory reactions (22, 36). Blocking such lysosomal escape could be beneficial under conditions when noninternalized/extracellular bacterial proliferation is blocked by antibiotic treatment. Blocking such receptors without antibiotic intervention is detrimental, because both SR-BI/II and CD36 KO mice were more sensitive to sepsis and bacterial infection in the absence of antibiotics (38). Based on such a hypothesis, we propose that blocking SR-B class receptors, either by L-37pA or using genetically manipulated mice defective in recep- tor expression, improves the outcomes of antibiotic/fluid-treated animals with severe infections/sepsis as the result of better contain- ment of bacteria by polymorphonuclear/granulocytic phagocytes. Extensive investigation will be required to determine how this mechanism interacts with many other mediators/pathways in the complex pathophysiology of sepsis (8, 51).

In the presence of antibiotic and fluid treatment, L-37pA reduced both systemic inflammation and tissue damage in CLP mice, L-37pA also improved mouse survival and profoundly increased neutrophil accumulation in the peritoneal cavity. Furthermore, an increased peritoneal neutrophil accumulation and a reduction in peritoneal bacterial proliferation were found in both CD36 and SR-BI/II KO mice. Both types of animals demonstrated improved organ function, reduced systemic inflammation, and increased ani- mal survival only when adrenal deficiency was appropriately compen- sated for with both MCs and GCs. In summary, our findings indicate that the absence or blockade of SR-B receptor family proteins can reduce both inflammation and tissue toxicity by diminish- ing bacteria-mediated damage to peritoneal phagocytes (mainly granulocytes). This enhances local granulocyte accumulation and bacterial containment, as well as reduces systemic inflammation and organ damage, leading to improved animal survival in sepsis.

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Disclosures
The authors have no financial conflicts of interest.

References


Supplemental Figure 1. Apoptotic cells in peritoneal lavage in septic scavenger receptor-deficient mice (CD-36 and SR-BI/II deficiency)

Peritoneal cells from lavage fluid were stained with anti-active caspase-3 antibody. The number of apoptotic cells was examined in ten randomly chosen 400X fields.
Supplemental Figure 2. Renal injury reduced in septic scavenger receptor-deficient mice (CD-36 and SR-BI/II deficiency)

Representative kidney histology results in sham (A), WT CLP (B), CD36-deficient mice CLP (C), WT CLP with steroid supplement (D) and SR-BI/II-deficient mice CLP with steroid supplement (E). (Original magnification x 400).
Supplemental Figure 3. L-37pA attenuates kidney injury

Representative kidney histology in sham (A), PBS control (B), L3D-37pA control peptide (C), L-37pA treatment peptide (D) (original magnification x 400).