Gut-Derived Lipopolysaccharide Promotes T-Cell–Mediated Hepatitis in Mice through Toll-Like Receptor 4

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Abstract

Robust clinical and epidemiologic data support the role of inflammation as a key player in hepatocellular carcinoma (HCC) development. Our previous data showed that gut-derived lipopolysaccharide (LPS) promote HCC development by activating Toll-like receptor 4 (TLR4) expressed on myeloid-derived cells. However, the effects of gut-derived LPS on other types of liver injury models are yet to be studied. The purpose of this study was to determine the importance of gut-derived LPS and TLR4 signaling in a T-cell–mediated hepatitis—Con A–induced hepatitis model, which mimic the viral hepatitis. Reduction of endotoxin using antibiotics regimen or genetic ablation of TLR4 in mice significantly alleviate Con A–induced liver injury by inhibiting the infiltration of T lymphocytes into the liver and the activation of CD4+ T lymphocytes as well as the production of T helper 1 cytokines; in contrast, exogenous LPS can promote Con A–induced hepatitis and CD4+ T cells activation in vivo and in vitro. Reconstitution of TLR4–expressing myeloid cells in TLR4-deficient mice restored Con A–induced liver injury and inflammation, indicating the major cell target of LPS. In addition, TLR4 may positively regulate the target hepatocellular apoptosis via the perforin/granzyme B pathway. These data suggest that gut-derived LPS and TLR4 play important positive roles in Con A–induced hepatitis and modulation of the gut microbiota may represent a new avenue for therapeutic intervention to treat acute hepatitis induced by hepatitis virus infection, thus to prevent hepatocellular carcinoma. Cancer Prev Res; 1–13. ©2012 AACR.

Introduction

Hepatocellular carcinoma (HCC) is the third leading cause of death from malignancy worldwide, and hepatitis B and C and associated liver cirrhosis represent major risk factors for HCC development. T-cell response has a vital role during hepatitis virus infection. Myriad data support the role of inflammation as a key player in HCC development (1). The inflammation can be triggered by tissue damage, infection, and toxin. Our previous data showed that gut-derived lipopolysaccharide (LPS) promote the inflammation during HCC development by activating Toll-like receptor 4 (TLR4) expressed on myeloid-derived cells (2).

However, the effects of gut-derived LPS and TLR4 on other types of liver injury models are yet to be studied.

Con A–induced hepatitis is a well-known experimental murine model with significantly elevated levels of transaminase as well as severe liver injury that can mimic many kinds of human T-cell–mediated hepatitis, such as virus hepatitis and autoimmune hepatitis (3–5). In Con A–mediated hepatitis model, activated T cells release a series of cytokines. Different cytokines can be categorized as T helper 1 (Th1) and T helper 2 (Th2)-associated cytokines by their biologic function. Studies have illustrated that Th1-associated cytokines such as interleukin (IL)-12 and IFN-γ are dominant factors inducing the development of Th1 cells (6). Conversely, IL-4 production directs the development of a Th2 response (7). Th1/Th2 differentiation of T cells is largely dependent on the balance of GATA-3 (8) and T-bet (9). The balance of Th1- and Th2-associated cytokines exerts a crucial role in normal immunoregulation and neoplastic outcome.

Emerging evidence suggests a strong interaction between the gut microbiota and human liver diseases (10, 11). Receiving approximately 70% of its blood supply from the intestine through the portal circulation, the liver is the first line of defense against gut-derived antigens (11). To cope with these latent systemic pathogens, the liver contains a large number of resident immune cells such as macrophages, natural killer cells, dendritic cells, and T and B lymphocytes (12). When normal liver physiology is
disrupted and inflammatory cells are activated, gut-derived factors likely augment or exacerbate certain liver diseases, leading to enhanced tissue damage and propagation of inflammation via activation of TLR-signaling pathways (13). The critical role of gut-derived endotoxin as a cofactor in acute and chronic liver diseases, both experimental and clinical, was already established more than 30 to 40 years ago (14). Our previous study also showed that the endotoxin/TLR4 regulates the survival and proliferation of hepatocytes and their preneoplastic derivatives during chemically induced hepatocarcinogenesis (2).

TLRs recognize pathogen-associated molecular patterns and activate signaling pathways that lead to the induction of innate immune and inflammatory genes (15). In addition, there is accumulating evidence that TLRs contribute significantly to the activation of adaptive immune responses such as dendritic cell maturation and T- and B-cell responses, specially, the TH1-dependent immune responses (16). TLR4 is an important member of TLRs, which could sense endotoxin and activate transcription factors that initiate innate immunity. TLR4 was also expressed on T lymphocyte, playing a vital role in adaptive immunity. Recent studies have shown the contribution of TLR4 signaling to the trapping of CD8+ T cells within the murine liver (17). Moreover, other studies indicate that direct interactions of gut-derived antigens signaling through TLR4 on CD4+ T cells contributes to their regulatory development and function (18).

In this study, we report that sustained LPS accumulation exacerbate Con A–induced hepatitis in mice. Both reduction of LPS using antibiotics regimen or genetic ablation of TLR4 can suppress the liver injury markedly. This attenuated mechanism is also involved in the protection of TLR4 endotoxin/TLR4 regulates the survival and proliferation of hepatocytes and suppressed activation of CD4+ T cells as well as decreased levels of Th1 cytokine production. In contrast, exogenous LPS challenge can significantly aggravate Con A–induced liver injury and promote activation of CD4+ T lymphocytes as well as secretion of Th1-associated cytokines. Reconstitution of TLR4-expressing myeloid cells in TLR4-deficient mice restored Con A–induced hepatic injury, indicating that myeloid cells are the major targets of LPS in this model. In addition, perforin/granzyme B mechanism is also involved in the protection of TLR4 ablation. These results suggest that preventing circulating endotoxin accumulation could have a beneficial impact on liver function for patients with T-cell–mediated hepatitis such as viral hepatitis, thus to prevent the development of HCC.

**Materials and Methods**

**Animals**

Male wild-type (wt; C57BL/10ScSnJ) and TLR4-deficient (TLR4−/−; C57BL/10ScNJ) mice were obtained from the Model Animal Research Center of Nanjing University, Nanjing, China. Male C57BL/6 mice (6–8 weeks old, weighing 18–22 g) and nonobese diabetic severe-combined immunodeficient (NOD/SCID) mice were obtained from the Shanghai Experimental Center, Chinese Science Academy, Shanghai, and maintained at an animal facility under pathogen-free conditions. All animals received humane care according to the criteria outlined in the “Guide for the Care and Use of Laboratory Animals” prepared by the National Academy of Sciences and published by the NIH (publication 86–23 revised 1985). For detailed information related to animal experiments, see the Supporting Experimental Procedures.

**Flow cytometry analysis**

Hepatic mononuclear cells or splenic cells were isolated and then labeled with anti-CD3-PE/CY7, anti-CD4-FITC mAb, and anti-CD69-APC mAb (BioLegend). Stained cells were assessed on a MoFlo XDP system (Beckman Coulter) equipped with Summit 5.1 Software. When assessing the activation of CD4+ T cells, CD4-positive subpopulation was first gated and the expression of CD69 in this population was determined. The results were shown as the proportion of CD4+ CD69+ cells in total CD4+ cells. For determination of proliferation of T cells, the isolated splenic cells were stimulated with Con A or purified anti-mouse CD3ε (BioLegend) in the presence of CFSE ( Molecular Probes) for the indicated period and then determined by flow cytometry.

**Isolation and Culture of CD4+ cells**

Complete RPMI-1640 medium supplemented with 10% heat-inactivated FBS, 2 mmol/L L-glutamine, 100 U/mL penicillin, and 100 μg/mL streptomycin was used throughout the experiments. Spleen-derived CD4+ T cells were negatively selected by using the CD4+ T cell isolation Kit (Stemcell Technologies). CD4+ T cells were stimulated with 5 μg/mL Con A or 200 ng/mL LPS or both. Twenty hours later, the cells were collected and stained with indicated antibodies for flow cytometry analysis.

**Statistics**

Data are expressed as means ± SE. Differences were analyzed by the Student t test, and P values less than 0.05 were considered significant.

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Figure 1. Antibiotics treatment suppresses Con A–induced liver injury and apoptosis in TLR4 intact mice. A, the serum LPS concentration at the indicated time after Con A injection in the untreated mice. , P < 0.05; , P < 0.001, 0 versus 20 hours. B, the serum LPS concentration at the indicated time after Con A injection in the antibiotics-treated mice and untreated mice. C, ALT and AST levels in mice of antibodies-treated and control group. D, H&E staining of livers from Con A–injected mice with or without antibiotics treatment. E, TUNEL assay of liver sections from antibiotics-treated and control mice. F, G, and H, livers were removed and lysed for Western blot with antibodies against the indicated proteins. G, expression of phospho-Erk1/2 in antibiotics-treated and control mice. H, ALT levels in TLR4−/− mice of antibiotics-treated and untreated groups after Con A administration. , P < 0.05; , P < 0.01. GAPDH, glyceraldehyde-3-phosphate dehydrogenase.
Figure 2. Deletion of gut-derived LPS suppresses T-cell infiltration, activation of CD4^+ T lymphocytes, and Th1-associated cytokines production. A, liver mononuclear cells were isolated from antibiotics-treated and control mice 0, 6, and 20 hours after Con A administration and percentage of CD3^+ cells were determined by flow cytometry. B, the percentage of activated CD4^+ T cells were determined by dual staining with CD4 and the activation marker CD69 followed by flow cytometric analysis. Percentages represent the proportion of CD4^+ CD69^+ cells in whole CD4^+ cells subpopulation. C and D, expression of Th1-associated cytokines (C) TNF-α, IFN-γ, IL-6, IL-2, and IL-12 and (D) Th2-associated cytokines IL-10 in the serum of antibiotics-treated mice and controls. *, P < 0.05; **, P < 0.01; ***, P < 0.001.
Results

Depletion of gut-derived LPS alleviates Con A–induced liver injury in TLR4 intact mice

Our previous study has shown that gut-derived endotoxin can promote DEN-induced liver injury and hepatocarcinogenesis (2), so we conjectured that gut-derived endotoxin may also impose a serious impact on other types of liver injury. To address this question, we chose the widely used Con A–induced hepatitis animal model, which mimics many kinds of human T-cell–mediated hepatitis. As shown

Figure 3. Exogenous LPS aggravates Con A–induced liver injury. A, mice were injected with Con A + LPS or Con A alone. At the indicated times, serum ALT levels were determined. B and C, the activation of CD4+ T cells (B) and serum levels of Th1-associated cytokines IL-2, TNF-α, IFN-γ, and IL-12 (C) in mice treated with Con A + LPS or Con A alone. D, expression of T-bet mRNA in livers of Con A-administrated mice treated with or without LPS. * P < 0.05; ** P < 0.01.
in the Fig. 1A, the serum levels of LPS were markedly elevated 6, 20 hours after Con A administration accompanied with severe liver inflammation and tissue injury, suggesting that serum endotoxin may be a critical cofactor in Con A–induced liver injury.

We next investigated whether circulating LPS exacerbates Con A–induced hepatitis. Mice were treated with a cocktail of nonabsorbable broad-spectrum antibiotics for 4 weeks (19) and then injected with Con A. Mice receiving this cocktail regimen showed reduced serum levels of LPS (Fig. 1B) and significant decrease in serum ALT and AST levels (Fig. 1C), indicating reduced liver damage in the antibiotics-treated mice than controls. This was confirmed by hematoxylin and eosin stain (H&E) and terminal deoxynucleotidyl transferase–mediated dUTP nick end labeling (TUNEL) staining, which showed reduced apoptosis and necrosis in the liver of antibiotics-treated mice (Fig. 1D and E). Reduced apoptosis was further confirmed by processing the pro–caspase-3 and PARP to the cleaved active form (Fig. 1F). Moreover, compared with control mice, the expression of antiapoptotic protein Mcl-1 was higher, whereas the proapoptotic protein Bax was lower in antibiotics-treated mice (Fig. 1F). Both Erk1 and Erk2 have important roles in regulating cell proliferation and cell differentiation (20). We found that the phosphorylation of Erk1/2 was significantly higher in antibiotics-treated mice (Fig. 1G) at 1 and 3 hours following Con A injection. These findings indicated that depletion of gut-derived LPS can protect the mouse from Con A–induced hepatitis. However, in the TLR4 (innate receptor of LPS)-deficient mice, depletion of gut-derived LPS had no protective roles in Con A–induced hepatitis, as there was no significant difference in serum ALT levels between the antibiotics-treated and untreated group (Fig. 1H).

In conclusion, these data definitely indicated that the gut-derived LPS can protect the mouse from Con A–induced hepatitis. However, in the TLR4 (innate receptor of LPS)-deficient mice, depletion of gut-derived LPS had no protective roles in Con A–induced hepatitis, as there was no significant difference in serum ALT levels between the antibiotics-treated and untreated group (Fig. 1H).

Depletion of gut-derived LPS suppresses T-cell infiltration and CD4⁺ T-cell activation

Next we analyzed the key pathways that were involved in Con A–induced injury. T cells, especially the CD4⁺ T cells, have been shown to play essential roles in the Con A–induced liver injury (3). We isolated liver mononuclear cells from the 2 groups and determined the percentage of CD3⁺ cells (T cells). As shown in Fig. 2A, after administration of Con A, the percentage of CD3⁺ cells was significantly lower in the antibiotics-treated mice compared with the control group, indicating that depletion of gut-derived LPS suppresses T-cell infiltration to liver. The activation of CD4⁺ T lymphocytes was determined by flow cytometric analysis of the early activation marker CD69. As shown in Fig. 2B, administration of Con A led to a significant increase in percentage of activated CD4⁺ cells (CD69⁺CD4⁺ cells in whole CD4⁺ subpopulation) in both groups, but it was lower in antibiotics group compared with control group, both at 6 hours (52.55% vs. 45.31%) and 20 hours (53.78% vs. 45.48%). These findings suggested that activation of CD4⁺ T cells is suppressed by depletion of gut-derived LPS.

Deletion of gut-derived LPS suppresses secretion of Th1-associated cytokines

Immune cells activated by Con A synthesize and secrete a series of inflammatory cytokines, and these cytokines are vital components of Con A–induced liver injury (3, 4). Using ELISA, expression of key Th1 cytokines such as TNF-α, IFN-γ, IL-12, IL-2, and IL-6, as well as Th2-associated cytokines IL-10 in the 2 groups were assessed. Fig. 2C shows that there is no difference in baseline of Th1-associated cytokines and Th2-associated cytokines at 0 hour; but at 3, 6, and 20 hours after Con A administration, the levels of Th1 cytokines in antibiotics-treated mice were much than in controls. Interestingly, Th2-associated cytokines IL-10 were much higher in antibiotics-treated mice than control mice (Fig. 2D). These data suggested that LPS may augment the Th1 response while inhibit the Th2 response to promote Con A–induced liver injury.

Exogenous LPS significantly aggravates Con A–induced liver injury

To further evaluate the contribution of LPS to the pathogenesis of Con A–induced liver injury, mice were co-injected with LPS and a low dose of Con A (10 mg/kg) or Con A alone. As shown in Fig. 3A, the ALT levels of the LPS + Con A-injected group were much higher than that of Con A group. Meanwhile, the proportion of activated CD4⁺ cells in mice treated with LPS + Con A was higher than the mice injected with Con A or exogenous LPS (80.75% vs. 62.04% vs. 5.30%; Fig. 3B). The Th1 cytokines such as IL-2, TNF-α, IFN-γ, and IL-12 were also elevated in the LPS + Con A group (Fig. 3C). To investigate the possible mechanisms of these findings, we evaluated the expression of T-bet (an important regulator of Th1 differentiation) by quantitative PCR. As shown in Fig. 3D, the expression of T-bet was significantly increased in Con A + LPS-treated mice compared with Con A–treated mice 3 hours after injection. These data suggested that LPS can promote Con A–induced hepatitis via promoting CD4⁺ T cells activation and Th1 cytokine production.
Figure 5. Deficiency in TLR4 does not affect T-cell proliferation but inhibits CD4⁺ T-cell activation following Con A injection in vivo and in vitro. A, liver mononuclear cells were isolated from wild-type and TLR4⁻/⁻ mice 0, 6, and 20 hours post Con A administration and percentage of CD3⁺ cells were determined by flow cytometry, ***, P < 0.01. B, the percentage of activated CD4⁺ T cells were determined by dual staining with CD4 and the activation marker CD69 followed by flow cytometric analysis. C, splenic cells isolated from wild-type and TLR4⁻/⁻ mice were stained with CFSE and cultured in the presence of Con A or anti-CD3 antibody. After 0, 24, and 48 hours of culture, cells were analyzed by fluorescence-activated cell sorting (FACS) for CFSE fluorescence. No significant differences were observed in splenic cell proliferation following Con A or anti-CD3 antibody treatment between wild-type and TLR4⁻/⁻ mice. D, isolated splenic cells from wild-type and TLR4⁻/⁻ mice were stimulated with Con A or LPS or Con A + LPS for 20 hours and stained for CD4 and CD69. Percentages represent the proportion of CD4⁺ CD69⁺ in whole CD4⁺ subpopulation. E, enriched spleen-derived CD4⁺ T cells were stimulated with Con A or LPS or Con A + LPS for 20 hours and stained for CD4 and CD69. Percentages represent the proportion of CD4⁺ CD69⁺ in whole CD4⁺ subpopulation.
TLR4 deficiency greatly attenuates Con A–induced liver injury

LPS exerts its effects primarily through its innate receptor TLR4; we then assessed the effect of TLR4 deficiency on Con A–induced hepatitis. Wild-type (wt) mice and TLR4 knockout (TLR4−/−) mice were injected with Con A intravenously and sacrificed 0, 6, and 20 hours thereafter. Analysis of liver histopathology revealed blunted inflammation and tissue injury in TLR4−/− mice compared with wild-type mice (Fig. 4A). This was confirmed by serum ALT and AST levels (Fig. 4B). TUNEL staining showed that more apoptotic cells were present in wild-type livers compared with livers from TLR4−/− mice (Fig. 4C). This was further confirmed by the activation of caspase-3 and PARP (cleavage form of caspase 3 and PARP; Fig. 4D). Moreover, as shown in Fig. 4E, TLR4 deficiency protected mice from a lethal dose of Con A: 66.7% of TLR4 wild-type mice died 9 hours after Con A injection, whereas 87.5% of TLR4−/− mice survived within 24 hours.

Besides, similar to the finding in the antibiotics-treated mice, Mcl-1 was much higher whereas Bax was much lower in TLR4−/− mice at 6 and 20 hours after Con A injection; the phosphorylation of Erk1/2 was significantly higher in TLR4−/− mice (Fig. 4F) at 1 and 3 hours following Con A injection. Taken together, these data showed that TLR4 deficiency protect the mouse from Con A–induced hepatitis.

Deletion of TLR4 suppresses T-cell infiltration and CD4+ T-cell activation following Con A administration

To further verify TLR4-dependent steps to aggravate Con A–induced hepatitis, we isolated liver mononuclear cells from wild-type and TLR4−/− mice following Con A injection and assessed the percentage of T cells and CD4+ T-cell activation by flow cytometric analysis. As shown in Fig. 5A, the percentage of CD3+ cells (T cells) was significantly elevated in wild-type mice compared with TLR4−/− mice after Con A injection. The activation of CD4+ T cells was also increased in wild-type mice compared with TLR4−/− mice both at 6 (77.45% vs. 66.77%) and 20 hours (60.00% vs. 30.69%; Fig. 5B). To rule out the possibility of the influence of TLR4 in cell proliferation, splenic cells isolated from wild-type and TLR4−/− mice were labeled with CFSE and incubated in the presence or absence of Con A or anti-CD3. After 0, 24, or 48 hours, splenic cell division was shown by CFSE dilution (Fig. 5C); there were no marked differences in splenic cell proliferation between wild-type and TLR4−/− mice. These data suggested that TLR4 may promote CD4+ T cells activation directly, other than promote T-cell proliferation.

Next we ask whether LPS can promote T-cell activation directly. Isolated splenic cells from wild-type and TLR4−/− mice were stimulated with 1 μg/mL Con A or 200 ng/mL LPS or both. Twenty hours later, the expression of CD69 was determined by flow cytometric analysis. As shown in Fig. 5D, the proportion of activated wild-type splenic cells stimulated with Con A and exogenous LPS was higher than that of the cells stimulated with Con A (77.09% vs. 66.86%). Conversely, in TLR4−/− cells, although it was all lower than that in the wild-type cells, there was no obvious difference in the proportion of activated CD4+ T cell between the 2 different treatments (Con A + LPS 62.35% vs. Con A 61.70%).

As T-cell response requires the antigen-presenting cells (APC), to rule out the probability that TLR4 expressed in APCs affects the CD4+ T cell activation, we isolated CD4+ T cells and carried out the stimulation experiment mentioned above. Similar data were observed in the enriched CD4+ T cell pool, in which more than 95% of splenic cells were positive for CD4 (Fig. 5E). These data indicated that LPS alone have little effect to activate T lymphocytes, but it could promote Con A–induced CD4+ T lymphocytes activation effectively, suggesting that LPS may have a direct role in the T-cell activation.

TLR4 ablation in bone marrow–derived cells alleviate Con A–induced liver injury

As TLR4 is expressed both on myeloid-derived cells and parenchymal cells in the liver, the difference of liver injury between wild-type and TLR4−/− mice might be caused by a bone marrow–derived cell or a resident liver cell such as hepatocytes, endothelial, or stellate cells. To rule out these possibilities, we carried out bone marrow transplantation experiments in the TLR4 knockout and wild-type mice. Five weeks later, the chimeric mice were injected with Con A and the liver injury and the activation of T cells in the liver was determined. As shown in Fig. 6A and B, both the Con A–associated liver injury and CD4+ T-cell activation were associated with bone marrow type: the chimeric mice with TLR4−/− marrow [TLR4−/−/TLR4−/− (TLR4−/− bone marrow→wt mice)] and TLR4−/−/wt (TLR4−/− bone marrow→wt mice)] showed milder liver injury and attenuated CD4+ T-cell activation. These data suggested that TLR4 expressed on myeloid cells played crucial roles in Con A–induced liver injury. To elucidate the role of TLR4 expressed on T cells in Con A–induced hepatitis directly, we carried out T-cell transfer experiment using the NOD/SCID mice (T cell, B cell, and NK cell deficient) according to the literature (21). As shown in Fig. 6C, adoptive transfer of wild-type T cells resulted in exacerbated Con A–induced liver damage in recipient mice compared with mice transferred with TLR4−/− T cells. These data showed that TLR4 expressed on T cells played key roles in Con A–induced hepatitis.

TLR4 deletion significantly reduces the production of Th1 cytokines

With ELISA, expression of Th1 cytokines such as TNF-α, IFN-γ, IL-12, IL-2, and IL-6, as well as Th2-associated cytokines IL-10, was assessed at 0, 3, 6, and 20 hours after Con A injection. Fig. 6D shows that there is no difference in baseline of Th1-associated cytokines and Th2-associated cytokines before Con A injection; however, after Con A administration, wild-type mice exhibited much higher levels of Th1 cytokines compared with TLR4−/− mice. Interestingly, Th2-associated cytokine IL-10 were much
higher in TLR4−/− mice in contrast to wild-type mice (Fig. 6D).

We also evaluated the expression of T-bet by quantitative PCR. As shown in Fig. 6E, T-bet expression showed no difference between wild-type and TLR4−/− animals before Con A administration; however, 1 and 3 hours after Con A injection, expression of T-bet was significantly increased in wild-type mice compared with TLR4−/− mice.

Taken together, our results showed a TLR4-related enhancement of key cytokines of the Th1 response, indicating that unusually prolonged exposure to these cytokines might exacerbate T-cell–mediated hepatitis. However, TLR4 deletion could significantly increase the production of IL-10, which can lighten Con A-induced liver injury.

Previous studies have identified that significant increases in proinflammatory cytokine expression aggravate the induction of apoptosis (22) via enhancing T lymphocyte cytotoxicity. Apoptosis induced by cytotoxic T lymphocyte has been proposed as a mechanism of tissue damage (23). An important pathway in T-lymphocyte–mediated cytotoxicity is the granule exocytosis of perforin/granzymes (24–26). To determine the role of granzyme b and perforin in Con A–induced liver injury, we measured their expression by qPCR. Our results showed that the expression of perforin was much higher in wild-type mice compared with the TLR4−/− mice (Fig. 6F). Furthermore, the levels of granzyme b were significantly higher in wild-type mice than in TLR4−/− mice, particularly 20 hours post Con A injection (Fig. 6F), indicating that the perforin/granzyme B pathway is a possible mechanism of augmenting Con A–induced liver injury by TLR4.

Discussion

Because of the anatomic links to the gut, there is a potential interrelation between the gut antigens, gut microbiota products (specifically endotoxin), and liver diseases. Although liver is constantly exposed to microbial products from the enteric microflora, no obvious inflammation occurs in the healthy liver. However, when normal liver physiology is disrupted and inflammatory cells are activated, gut-derived factors likely augment or exacerbate certain liver diseases leading to enhanced tissue damage and propagation of inflammation. Activation of innate immunity, specifically TLR4 signaling, has emerged as a central component of the inflammatory response of the liver to gut bacteria under pathologic conditions (13, 27). Abundant data show that TLR4 ligand, endotoxin, is elevated in experimental models of hepatic fibrosis (28) and patients with chronic liver diseases (29, 30). We have now observed that serum endotoxin levels were elevated in an immune-mediated liver injury model. This endotoxin may result from (i) decreased clearance of LPS, hepatocyte damage and reticuloendothelial system (mainly the Kupffer cells) dysfunction induced by Con A; (ii) increased gut permeability: the detoxification ability of liver is reduced because of the liver damage. Indeed, gut barrier dysfunction leading to elevated intestinal permeability is also considered the main cause of endotoxia in alcoholic liver disease (31) and has an important role in LPS/GalN-induced fulminant hepatitis (32); (iii) bacteria overgrowth and translocation. Con A is a potent T-cell mitogen with tropism for the liver. In mice, Con A induces a severe liver injury that is a model of human T-cell–mediated hepatitis, which is dependent on the activation of CD4⁺ lymphocytes (3) and requires Th1 cytokines such as IL-2, IFN-γ, and TNF-α. It is reported that deficiency of Toll signaling resulted in failure to generate Th1-dependent immune responses (16), and TLR4 also plays vital roles in the function of CD4⁺ and CD8⁺ T cells (17, 18). Using antibiotics to reduce the LPS levels and TLR4 knockout mice, we showed that gut-derived LPS can promote Con A–induced liver injury in TLR4-dependent manner. Our data suggest that this effect is mediated partly by activation of CD4⁺ T cells: both depletion of LPS and TLR4 ablation can suppress the infiltration of T lymphocytes into liver and activation of CD4⁺ T cells in vivo, whereas exogenous LPS exacerbates Con A–induced liver injury and promotes activation of CD4⁺ T lymphocytes induced by Con A. As LPS augments Con A–induced wild-type CD4⁺ T-cell activation and the activation of TLR4−/− CD4⁺ T cells stimulated with Con A in vitro is suppressed, it is reasonable to speculate that LPS has a direct role in T-cell activation through TLR4, may be a costimulatory role, just like TLR2 (33). The BMT experiment further indicated that TLR4 expressed on myeloid cells other than the resident liver cells plays crucial roles in the Con A–induced liver injury. Moreover, the result of T-cell transfer experiment also showed that TLR4 expressed on T cells played key roles in Con A–induced hepatitis. Therefore, even though T cell is not the only effective cell type originated from bone marrow involved in Con A–induced hepatitis (3, 34), their activation augmented by gut-derived LPS through TLR4 plays vital role in this hepatitis model. However, more detailed mechanisms need to be further investigated.

Our previous study on TLR4 and HCC used the carcinogen diethylnitrosamine (DEN) to induce hepatitis and showed that TLR4−/− mice had aggravated liver injury after DEN treatment. However, in this work, TLR4 knockout showed decreased liver injury induced by Con A. The reasons for this difference may be in terms of the acute liver damage induced by DEN; TLR4 activation (by LPS, and

Figure 6. TLR4 expressed on bone marrow–derived cells promotes Con A–induced liver injury. A, bone marrow–transplanted chimeric mice were treated with Con A, and the serum ALT was measured at indicated times. n = 6–8. B, liver mononuclear cells were isolated from chimeric mice at the indicated times post Con A administration. The activation of CD4⁺ T cells was determined by the flow cytometry. C, NOD/SCID mice with transferred T cells were treated with Con A, and the serum ALT was measured 6 hours later. n = 6–8. *, P < 0.05; D, the expression of Th1-associated cytokines IL-2, TNF-α, IFN-γ, IL-12, IL-6, and Th2-associated cytokines IL-10 were determined by ELISA. n = 6–8. E, expression of T-bet mRNA in wild-type and TLR4−/− liver. F, expression of perforin and granzyme b mRNA in wild-type and TLR4−/− liver 0, 6, or 20 hours after Con A treatment. *, P < 0.05; **, P < 0.01; ***, P < 0.001.
others) on hepatocytes could protect them from apoptosis by induction of antiapoptotic proteins, such as Bcl-xl and A20. TLR4 deficiency, therefore, ablated the protective effects of both LPS and endogenous ligands on hepatocytes, thus leading to more severe liver damage. However, in the Con A model, the BMT experiment showed that TLR4 expressed on myeloid cells played major roles in liver damage. On the other hand, Con A is a more potent inducer of liver damage than DEN: Con A hepatitis is a fulminant hepatitis, the Con A–treated mice usually died within several hours, whereas the DEN was a milder liver poison and does not lead to death at the dosage we used (100 mg/kg).

T-lymphocyte–associated cytokine production has previously been shown to be critical for the injury response. Th1 and Th2 cytokines are antagonistic in activity and their balance and regulation is crucial for the immune response (6, 7). However, in pathologic conditions, such as allergic and autoimmune diseases, polarized Th1 and Th2 responses are found and believed to be critical to the outcome of these conditions (8). Here we found that exogenous LPS promotes Th1 cytokine production induced by Con A through TLR4, whereas reduction of LPS using antibiotics or the absence of TLR4 reinforces the expression of Th2 cytokines. T-bet is a powerful transcription factor involved in Th1 development (9). Our results suggested that LPS promotes Con A–induced expression of T-bet through TLR4. The Th1 cytokines, particularly TNF-α, are important cytotoxic mediators. It is conceivable that the elevated Th1-associated cytokines promote Con A–induced cellular immunity and aggravate liver tissue damage. Moreover, T lymphocyte cytotoxicity has been proposed as mechanism of apoptosis (25, 26). An important pathway in T-lymphocyte–mediated cytotoxicity is the granule exocytosis of perforin/granzymes (26). In this study, we found that TLR4 regulates perforin and granzyme b expression, indicating the important role of TLR4 in hepatocytes apoptosis through enhancing T lymphocyte cytotoxicity.

It has been shown that immune cells contribute to liver tumorigenesis. CD4+ or CD8+ T cells expressing inflammatory cytokines as well as cytolical proteins contribute to hepatocyte death, tissue remodeling, and transformation, finally leading to HCC (35, 36). Compared with other causes of cirrhosis, immune-mediated hepatitis is associated with a higher risk of developing HCC. Here we present a new feature of LPS/TLR4 signaling in T cells using the Con A–induced hepatitis model: gut-derived LPS have a direct role in promoting T lymphocyte activation through TLR4. Our data suggest that modulation of the gut microbiota and lessening the gut translocation of endotoxin may represent a new avenue for therapeutic intervention to treat or prevent immune-mediated hepatitis. Therefore, it will be interesting to determine whether the regimen with antiendotoxin effects will prove beneficial in preventing or delaying T-cell–mediated hepatitis and hepatitis-induced HCC.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Authors’ Contributions

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Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): Y. Lin, L.-X. Yu, W. Yang, Y.-Q. He

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Hepatitis in Mice through Toll-Like Receptor 4 Mediated Gut-Derived Lipopolysaccharide Promotes T-Cell–Mediated Hepatitis in Mice through Toll-Like Receptor 4

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