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Involvement of Innate and Adaptive Immunity in a Murine Model of Coronary Arteritis Mimicking Kawasaki Disease

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Kawasaki disease (KD) is the most common cause of acquired cardiac disease and acute vasculitis in children in the developed world. Injection of a cell wall extract isolated from Lactobacillus casei (LCCWE) into mice causes a focal coronary arteritis that histopathologically mimics the coronary lesions observed in KD patients. In this study we used this model to investigate the participation of T cells, B cells, and dendritic cells (DC) in the development of coronary arteritis. RAG1−/−, B cellnull, and wild-type (WT) mice were injected with a single dose of LCCWE (500 μg/mouse i.p.). None of the RAG1−/− mice developed coronary arteritis, whereas 70% of WT and 100% of B cellnull mice developed coronary lesions, indicating that T cells were required for lesion formation. When splenocytes isolated from LCCWE-treated mice were restimulated with LCCWE, we observed significant IFN-γ secretion in WT but not in RAG1−/− mice. Immunohistochemical staining showed F4/80+ macrophages, activated MDC-8+ myeloid DCs (mDC), plasmacytoid DCs, and colocalization of CD3 T cells with mDCs in coronary artery lesions, suggesting an Ag-driven process. T cells but not B cells are required for LCCWE-induced coronary arteritis. Similar to human lesions, the coronary lesions contain macrophages, activated mDCs, and plasmacytoid DCs all in close proximity to T cells, further strengthening the relevance of this mouse model to the immunopathology of coronary disease in KD. These studies are consistent with the interpretation that macrophages and DCs may collaborate with T cells in the pathological mechanisms of coronary arteritis. The Journal of Immunology, 2009, 183: 5311–5318.
ago, Lehman et al. (24, 25) reported that a single i.p. injection of a cell wall extract isolated from Lactobacillus casei (LCCWE) reproducibly leads to the development of proximal coronary arteritis that is histopathologically very similar to the coronary arteritis observed in human KD. Moreover, as in children with KD (8, 21, 22), coronary arteritis in LCCWE-treated mice responds to therapy with IVIG (25, 26) and is suppressed by treatment with Abs against TNF-α (27, 28).

We (15) and others (26, 28–32) have used this model to test potential mechanisms that might cause KD. Our studies have identified innate immune signaling pathways that are required for the development of LCCWE-induced arteritis (15). Specifically, intact innate immune signaling via TLR2 and Myd88 was necessary for mice to develop coronary arteritis. Acute KD coronary arteritis is characterized by transmural infiltration of CD4 and CD8 T lymphocytes and macrophages and notable absence of B cells (33). In a recent study, we demonstrated that coronary artery lesions of KD patients contain increased numbers of mature and activated myeloid DCs with high HLA-DR expression and frequent T cell contacts detected immunohistochemically (IHC), suggesting that myeloid dendritic cells (mDC) might be activating T cells in situ (16). These findings support the concept that both innate and adaptive immunity participate in the pathophysiology of this vasculitis.

Here we tested the hypothesis that adaptive immunity is also required for the development of LCCWE-induced coronary arteritis. We also wished to determine whether macrophages, DCs, and T cells are also present in the histological lesions observed in this mouse model similar to findings as we and others have described in KD patients (16). Our results indicate that T cells are essential for development of arteritis, but B cells are not. Furthermore, similar to findings in KD patients (16, 33), we show infiltration of mouse coronary lesions with T cells, mDCs, plasmacytoid DCs (pDC), and macrophages, all of which participate in innate and adaptive immunity. These observations further strengthen the relevance of this LCCWE-induced KD mouse model in mimicking the histopathological findings of the coronary lesions seen in KD patients and provide important new data suggesting the type of immunity participate in the pathophysiology of the mouse model of KD as well as clinical KD.

Materials and Methods

Preparation of LCCWE

Group B L. casei (ATCC 11578) were grown in Lactobacillus MRS broth (Difco), harvested by centrifugation during the exponential growth phase, and washed with PBS at pH 7.4. The bacteria were then disrupted by overnight incubation at room temperature in 4% SDS; the cell wall extract was prepared as described earlier (15). Bacteria were manually crushed between frosted ends of sterile glass slides (VWR International), the resulting suspensions were filtered through a 70-µm pore size nylon cell strainer (BD Falcon), and RBCs were lysed using RBC lysis buffer (eBioscience). LCCWE and the cell wall content of the supernatant was determined by a colorimetric phenolsulfuric acid extraction technique and expressed as milligrams of total rhamnose amount as determined above in PBS or PBS alone (controls). Mice were sacrificed 21 days later; hearts were removed, perfused with PBS, and embedded in optimal cutting temperature (OCT) compound. Coronary arteries were identified in serial sections (6 µm) stained with H&E (80–100 sections of the heart per mouse). We analyzed 6–10 sections for each animal showing the aortic root and coronary sections. Blinded assessment of the histopathology of the coronary arteries and aortic root was performed as described earlier (15), with particular emphasis on the region in proximity to the ostium of the coronary arteries. No coronary aneurysms were observed in these mice because they were sacrificed before aneurysm development.

Splenic lymphocytes and cytokine release

Preparation of LCCWE

Splenocytes (0.5 × 10^6) were seeded into 96-well plates (BD Falcon) at a final volume of 200 µl/well. Cells were stimulated with LCCWE (5 µg/ml, 1 µg/ml, 200 ng/ml, or 40 ng/ml) or control medium for 72 h. IFN-γ secretion was measured by ELISA (eBioscience) using the manufacturer’s suggested protocol.

Expression of cytokine release

Preparation of LCCWE

Splenocytes (0.5 × 10^6) were seeded into 96-well plates (BD Falcon) at a final volume of 200 µl/well. Cells were stimulated with LCCWE (5 µg/ml, 1 µg/ml, 200 ng/ml, or 40 ng/ml) or control medium for 72 h. IFN-γ secretion was measured by ELISA (eBioscience) using the manufacturer’s suggested protocol.

Assessment of cytokine release

Preparation of LCCWE

Splenocytes (0.5 × 10^6) were seeded into 96-well plates (BD Falcon) at a final volume of 200 µl/well. Cells were stimulated with LCCWE (5 µg/ml, 1 µg/ml, 200 ng/ml, or 40 ng/ml) or control medium for 72 h. IFN-γ secretion was measured by ELISA (eBioscience) using the manufacturer’s suggested protocol.

Assessment of DCs, macrophages, and T cells in the coronary arteritis sections in LCCWE-injected mice

Frozen heart sections were IHC analyzed for DC, macrophage, and T cell infiltration. Rat anti-mouse MHC class II Ab (Serotec), specific for mature monocytes and macrophages, was used to identify PDCA-1-positive cells, and CD11c-specific Ab (Chimeragene) for RIP1/480 (Serotec) specific marker for macrophages (39), and anti-mouse CD3, a T cell marker, were used as described earlier (17). IgG2a and IgG2b were the isotype controls (Serotec).

Computer-assisted image analysis

Digital images were taken at a magnification of ×300 with a charge-coupled device camera (Nikon DXM 1200) of three consecutive sections of the aortic root and coronary artery. DCs, macrophages, and T cells in lesions were quantified by computer-assisted histomorphometry (Image-Pro Plus; Media Cybernetics). For each analysis, the color threshold for immunostained cells was manually adjusted in the images until the computerized detection matched visual interpretation. The numbers of immunostained cells were digitally counted in the defined area (0.25 µm²) of the aortic root/coronary artery section. For each cell type, the mean cell number was calculated (n = 3) out of the corresponding three consecutive sections for each animal (three animals/group). Microscopic analyses were performed independently by two different investigators, and intra- and interobserver coefficients of variabilities were <10%.

GM-CSF expression in whole heart cells stimulated with LCCWE

The whole heart was harvested, minced, and digested to a single-cell suspension. Hearts were harvested from WT, TLR2−/−, and Myd88−/− mice and were stimulated with 20 µg/ml LCCWE or 10 ng/ml LPS in vitro. Six hours later, total RNA from heart cells were isolated using RNAeasy mini kit (Qiagen) and probed using mouse cardiovascular disease array II (atherosclerosis cDNA gene array) following the manufacturer’s recommendations (SuperArray Bioscience). Analysis of the images and quantification were performed by the GE array expression analysis suite software.
genes of interest were normalized to the housekeeping gene GAPDH.

GM-CSF induction by LCCWE in murine endothelial cells (EC)

Primary murine aortic ECs were isolated and purified to >95% purity from WT, MyD88−/−, TLR2−/−, and TLR4−/− mice as we previously described (40, 41). ECs were grown to 80% confluency and stimulated overnight with LCCWE (10, 20 g/ml) or LPS (10 ng/ml). GM-CSF release into the cell-free supernatant was determined after 24 h of treatment by ELISA (eBioscience) as described (42).

Statistical analysis

Data are expressed as means ± SEM. Statistical significance was determined by Student’s t test and/or one-way ANOVA for multiple comparisons. A p value of <0.05 was considered statistically significant.

Results

T cells are present in LCCWE-induced coronary arteritis

In patients, acute KD coronary arteritis is characterized by infiltration of T lymphocytes (33). To assess the presence of T cells infiltrating the coronary lesions in this mouse model, we performed IHC staining for CD3+ cells in LCCWE-injected mice. As shown in Fig. 1, A and D, LCCWE-injected WT mice showed a significantly increased presence of CD3+ cells in the proximity of the aorta and coronary artery lesions. Isotype control (IgG2a) did not show any positive staining (Fig. 1C). No CD3+ T cells were observed in coronary arteries of PBS-injected control mice (Fig. 1B).

RAG1−/− mice do not develop LCCWE-induced coronary arteritis

To better elucidate the role of the adaptive immunity in the development of coronary arteritis in the mouse model, we used RAG1−/− mice, which do not possess mature T cells or B cells owing to faulty VDJ recombination (43). Injection of LCCWE induced severe focal acute coronary arteritis in 7 of 10 WT mice (Table I and Fig. 2A). Histological results obtained from WT mice 21 days post-LCCWE injection appeared qualitatively similar to those we reported previously in WT mice (15, 24). The coronary lesions consisted of a localized, nodular infiltrate of acute and chronic inflammatory cells localized to the most proximal portion of the coronary artery. Often, the combination of inflammation and intimal proliferation resulted in complete occlusion of the arterial lumen (Fig. 2A). In contrast, we observed a complete absence of inflammatory infiltrates in the coronary arteries of the LCCWE-injected RAG1−/− mice (Table I and Fig. 2B), which appeared histologically indistinguishable from the PBS-injected WT mice (Fig. 2C). These observations indicate that adaptive immune system (T and/or B cells) is required in LCCWE-induced coronary lesion formation.

B cells are not required for LCCWE-induced coronary arteritis

To determine whether T cells, B cells, or both are required to trigger coronary arteritis, we injected B cell-deficient mice (35).
with LCCWE or PBS vehicle only (Fig. 3C). These B cell-null mice have a mutation that blocks B cell development at the pro-B stage (35). Almost 70% of B cell-null mice developed coronary lesions. Histological analysis revealed a severe inflammatory cell influx into coronary artery lesions (Fig. 3, A and B). Intimal proliferation and massive infiltration of inflammatory cells was observed and tended to occlude the artery lumen (Fig. 3, A and B). B-null LCCWE-injected mice showed histopathology similar to that of WT LCCWE-injected mice. Increased inflammatory cells were also detected at the level of the myocardium immediately adjacent to the coronary artery (Fig. 3A). These results indicate that T cells are required to produce coronary arteritis after LCCWE injection, but B cells are unnecessary. A summary of the coronary lesion development can be found in Table I.

In vitro restimulation with LCCWE induces IFN-γ secretion by splenocytes isolated from LCCWE-injected WT but not RAG1−/− mice

Because IFN-γ expression is a hallmark of a Th1 response (44), we wished to determine Ag-specific recall responses in WT and RAG1−/− mice by measuring IFN-γ release from splenocytes following LCCWE restimulation ex vivo. We harvested splenocytes 7 days after injection of LCCWE into WT, RAG1−/−, or B-null mice. We restimulated these cells with LCCWE (5 μg/ml, 1 μg/ml, 200 ng/ml, or 40 ng/ml). WT and B-null splenocytes showed a significant increase in IFN-γ release after LCCWE stimulation (p < 0.01; Figs. 4, A–C). However, RAG1−/− splenocytes produced very low levels of IFN-γ compared with the medium-treated WT-derived splenocytes (Fig. 4B). In control experiments, IFN-γ secretion was not detectable from splenocytes, obtained from PBS-treated WT mice and stimulated with LCCWE (Fig. 4A). These results indicate that T cells are required to produce a specific response to LCCWE, which in turn suggests that the adaptive immune system is involved in the pathological mechanism mediating coronary arteritis. Although B cell-null splenocytes restimulated with LCCWE still produced a significant amount of IFN-γ, the level was slightly reduced compared with that of WT splenocytes. This was probably due to the fact that B-cells can act as weak APCs. Although these results suggest that B cells are not essential in LCCWE-induced arteritis, it does not rule out any potential role B cells may play in this model.

Both activated mDCs and pDCs as well as macrophages are present in LCCWE-induced coronary artery lesion

Significant numbers of mDCs accumulate in coronary lesions in patients with KD, particularly in the intimal layer of affected arteries as we have recently reported (16). To determine whether this also occurs in the LCCWE-induced coronary arteritis mouse model that mimics the human KD lesions, we performed IHC analyses using Abs against MIDC-8 to identify mDCs (36, 37) PDCA-1 Ab to identify pDCs and F4/80 to identify macrophages in the mouse coronary lesions (39). As shown in Fig. 5, A and D, macrophages were significantly more...
numerous in the proximal coronary arteries of LCCWE-injected mice in those of PBS-injected controls (Fig. 5B). Similarly, significantly increased infiltration of myeloid MIDC-8 positive DCs (mDCs) was observed in LCCWE-induced coronary lesions (Fig. 6, A and D) but not in PBS-treated control mice (Fig. 6B). Isotype controls for macrophage and mDC staining did not show any positive staining (Figs. 5C and 6C). PDCA-1 immunostaining also showed significantly increased numbers of infiltrating pDCs in coronary artery lesions after LCCWE injection in WT mice compared with PBS-injected control mice (Fig. 7, A and D), and isotype controls were negative (Figs. 7, B and C). These data suggest that, like human coronary artery lesions obtained from KD patients, the LCCWE-induced coronary arteritis mouse model also mimics the mDC, pDC, and macrophage infiltration in close proximity to T cells, further validating this mouse model. The results also imply Ag presentation and an ongoing Ag-specific inflammatory response to LCCWE in the coronary artery lesions.

**LCCWE induces GM-CSF gene and protein expression in mouse aortic endothelial cells in a TLR2- and MyD88-dependent manner**

We have previously reported that LCCWE-induced coronary lesions are absent in TLR2<sup>−/−</sup> or MyD88<sup>−/−</sup> mice, suggesting the critical role of the TLR2/MyD88 innate immune signaling pathway in development of lesions (15). A recent study reported that GM-CSF plays a key role in DC migration into atherosclerotic lesions and that lack of GM-CSF in hypercholesterolemic mice resulted in smaller atherosclerotic lesions and a drastic decrease in the numbers of DCs accumulating in these atherosclerotic plaques (45). Considering atherosclerosis is another inflammatory condition of the arteries, including the coronaries, we wished to investigate whether LCCWE could stimulate expression of GM-CSF in endothelial cells, which in turn might lead to increased recruitment of DCs to coronary artery lesions in our mouse model amplifying the inflammatory response. To test this possibility we isolated primary mouse aortic ECs from WT or TLR2, TLR4, or MyD88<sup>−/−</sup> mice, and stimulated these cells with LCCWE (or PBS), and assessed GM-CSF secretion. LCCWE significantly increased GM-CSF release in WT mouse aortic ECs, whereas there was a significantly reduced GM-CSF release from ECs obtained from...
TLR2\(^{-/-}\) or MyD88\(^{-/-}\) mice (Fig. 8A). Furthermore, we also observed significantly increased GM-CSF gene expression (>3-fold increase) in whole heart cells from mice treated with LCCWE ex vivo when compared with PBS-treated controls, and the GM-CSF gene expression was significantly decreased in hearts obtained from TLR2\(^{-/-}\) and MyD88\(^{-/-}\) mice, which are resistant in LCCWE-induced coronary lesions (Fig. 8B). These results suggest that the differential induction of LCCWE-induced GM-CSF production may play a role in the recruiting and/or retaining activated DCs in the coronary lesions of LCCWE-injected mice.

**Discussion**

KD is now recognized as the leading cause of acquired heart disease in children in the United States and the developed world (1, 3). The underlying etiology and mechanisms leading to medium and small vessel inflammatory response and coronary artery lesions and aneurysms that are the hallmarks of KD are largely unknown. Furthermore, it is unclear how and why acute systemic immune activation leads to chronic inflammatory arterial damage that localizes to the coronary arteries. The activation of the immune system in KD seems to encompass both the innate and adaptive immunity. Both human studies and animal models indicate the presence of various activated immune cells in coronary artery lesions (15, 16, 23–28, 30, 31, 46, 47). Intact innate immune signaling pathways are essential for such lesions to develop (15). Neutrophils are present in the early phase of the inflammatory pattern, rapidly followed by macrophages, DCs, plasma cells, and T cells (33, 48). Over the years, considerable evidence has accumulated to suggest that T cells play a significant role in the pathogenesis of KD, and several studies have documented the presence of infiltrating T lymphocytes in the human coronary artery lesions (33, 49). We have also shown that human coronary lesions obtained from children with fatal KD have significant numbers of mature, activated mDCs, pDCs, and macrophages in close contact with CD3\(^+\) T cells, suggesting and Ag-driven adaptive immune process (16).

There are striking similarities in the histopathology and kinetics of disease between human KD and the LCCWE-induced coronary arteritis mouse model (23–25, 27, 47). Initially, we analyzed the specific innate and adaptive immune responses and infiltrating cell types between the human and mouse model of coronary artery disease.
lesions. We have shown that LCCWE-induced coronary arteritis in mice requires intact signaling via TLR2 and MyD88, both of which are key participants in innate immunity (15). However, those studies did not address the potential participation of an acquired immune system in the mouse model of coronary arteritis.

Here we report direct evidence indicating that acquired immune mechanisms participate in the development of LCCWE-induced coronary arteritis in mice. We show that T cells but not B cells are required for development of arteritis. Coronary artery lesions in LCCWE-injected mice showed positive CD3 immunostaining, but more importantly, no RAG1−/− mice develop coronary lesions after LCCWE treatment. In contrast, B cell-deficient mice developed arteritis at the same frequency and severity as WT mice. Because RAG1−/− mice have no T cells or B cells, these results indicate that T cells are essential for coronary arteritis to develop, but B cells are not. The fact that B cells are dispensable in turn indicates that an Ab-mediated response either did not occur or was a nonessential contributor to the pathophysiology of the disease. Our results therefore strongly implicate a major role for T cells in this murine model of coronary arteritis, and suggest that the same is likely true for patients with KD, because in both cases the lesions contain subpopulations of the same lymphocytes (16, 33).

Splenocytes from LCCWE-treated RAG1−/− mice failed to produce IFN-γ when restimulated ex vivo. LCCWE causes increased local expression of IFN-γ in affected arteries in a biphasic manner, with an initial spike 3 to 7 days after LCCWE, then a late spike at 28–42 days (50). However, IFN-γ expression in the arterial lesion does not appear to be essential for development of lesions, given that LCCWE can still induce coronary lesions in IFN-γ-deficient mice (50). Nevertheless, our ex vivo results where restimulation of splenocytes with LCCWE elicited IFN-γ production clearly support the interpretation that direct activation of Ag-specific T cells occurs in response to LCCWE treatment and invariably accompanies development of arteritis. Because T cells produce a variety of cytokines and chemokines, it seems reasonable to surmise that IFN-γ is redundant, because even when T cells are genetically incapable of producing IFN-γ, they can still promote focal arteritis after LCCWE treatment (50). Consistent with this concept, another study reported that both TNF-α receptor knockout mice and WT mice treated with the TNF-α blocking agent etanercept were protected from development of coronary lesions (31). These results are consistent with the interpretation that TNF-α is necessary for induction of coronary artery inflammation and aneurysm formation in the LCCWE-induced coronary arteritis mouse model. TNF-α-blocking agents have also been successfully used clinically in KD patients refractory to standard treatment with IVIG and aspirin (51), suggesting that TNF-α expression may similarly be required for the development and/or progression of coronary lesions in clinical KD.

In addition to T cells, we also observed that mDCs, pDCs, and macrophages accumulate in the coronary artery lesions in LCCWE-injected mice. All of these cell types are key contributors to innate and adaptive immunity. These findings are very similar to observations we described on human coronary artery tissues obtained from KD patients (16). Collectively, these previous studies (15, 16) and results reported here strongly implicate the involvement of both innate and adaptive immune mechanisms in LCCWE-induced coronary arteritis and thus suggest that both arms of the immune system also participate in the pathophysiology of clinical KD. Not only did we find pDCs in the coronary lesions in both coronary artery lesions of KD patients (16) and LCCWE-injected mice, but also in both cases pDCs were colocalized with mDCs, suggesting that activation of mDCs could lead to exacerbation of the coronary lesions. Previous studies investigating the role of pDCs in human atherosclerosis, another example of focal arterial inflammatory disease (52, 53), similarly found clustering of pDCs with mDCs in atherosclerotic plaques leading to enhanced cytotoxic T cell responses. Furthermore, production of IFN-α by pDCs increased expression of TNF-α in atherosclerotic plaques, thus exacerbating the arterial inflammation (54). Therefore, it is tempting to speculate that in both atherosclerotic coronary artery plaques and in KD lesions, pDCs may amplify focal inflammation and may contribute to the development and progression of these vascular lesions. However, this possibility requires further study.

Recently, Shaposhnik et al. (42, 45) showed that GM-CSF plays a key role in DC migration into atherosclerotic lesions in hypercholesterolemic mouse models of atherosclerosis and that mice deficient in GM-CSF exhibit both diminished lesion size and significantly decreased DC accumulation in the atherosclerotic plaques. Indeed, we recently reported that DC accumulation in Chlamydia pneumoniae-mediated acceleration of atherosclerotic lesions in the aortic root of ApoE-null mice were related to bacteria-induced GM-CSF production (42). Similarly, here we observed that LCCWE induced a dose-dependent expression and release of GM-CSF in murine primary aortic ECs in a TLR2- and MyD88-dependent manner. Therefore, it is tempting to propose that the LCCWE-induced GM-CSF production may play a role in the migration and accumulation of DCs into the coronary artery lesions that we observed in this mouse model of arteritis.

In conclusion, we demonstrate that both innate and adaptive immunity are essential for development of coronary lesions in the LCCWE mouse model of coronary arteritis, and that although T cells are essential, B cells are dispensable. Additionally, we highlight the histological similarities between this mouse model of coronary arteritis and human coronary artery lesions seen in patients with KD, providing further validation for the use of this model to study the immunopathology of coronary lesions of KD. These findings expand our understanding of the cellular mechanisms regulating immune activation and localized inflammation in the coronary arteries, which may potentially lead to improved treatments and to minimize the long-term morbidity and mortality in children with KD.

Disclosures

The authors have no financial conflict of interest.

References


