Inducible costimulator is essential for collagen-induced arthritis

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CD4⁺ helper Th cells play a major role in the pathogenesis of rheumatoid arthritis. Th cell activation, differentiation, and immune function are regulated by costimulatory molecules. Inducible costimulator (ICOS) is a novel costimulatory receptor expressed on activated T cells. We, as well as others, recently demonstrated its importance in Th2 cytokine expression and Ab class switching by B cells. In this study, we examined the role of ICOS in rheumatoid arthritis using a collagen-induced arthritis model. We found that ICOS knockout mice on the DBA/1 background were completely resistant to collagen-induced arthritis and exhibited absence of joint tissue inflammation. These mice, when immunized with collagen, exhibited reduced anti-collagen IgM Ab’s in the initial stage and IgG2a Ab’s at the effector phase of collagen-induced arthritis. Furthermore, ICOS regulates the in vitro and in vivo expression of IL-17, a proinflammatory cytokine implicated in rheumatoid arthritis. These data indicate that ICOS is essential for collagen-induced arthritis and may suggest novel means for treating patients with rheumatoid arthritis.

sitive to experimental autoimmune encephalomyelitis (EAE) (16). Therefore, ICOS appears to play opposite roles in humoral and inflammatory responses. The function of ICOS in Ab-mediated autoimmune diseases such as RA has not been addressed, however.

In this paper, we have analyzed the role of ICOS in RA using the CIA model. We found that ICOS knockout mice on the DBA/1 background were completely resistant to CIA. Compared with ICOS+/+ mice, ICOS−/− exhibited reduced anti-collagen IgM and IgG2a titers, indicating that ICOS regulates to some extent the humoral responses. Furthermore, ICOS regulates the expression of IL-17 in vitro and in vivo. Therefore, ICOS plays an important role in the pathogenesis of CIA; it therefore provides an important and novel target for therapy of RA patients.

Methods

Mice. ICOS knockout mice were backcrossed six generations onto the DBA/1 background. ICOS+/+ and ICOS−/− mice, all on F6 backcross, were interbred, and their offspring were used for the experiments. All mice were 8–10 weeks old at the time of immunization. The mice were housed in a specific pathogen-free facility.

Induction of collagen-induced arthritis. Arthritis was induced and scored in male ICOS+/+ and ICOS−/− mice by immunizing with CII (Sigma-Aldrich, St. Louis, Missouri, USA) (19). Chicken CII was dissolved in cold 10 mM acetic acid overnight at 4°C and emulsified with equal volume of CFA (Sigma-Aldrich) to give a final concentration 1 mg/ml. Experimental mice were immunized intradermally at the base of the tail with equal volume of CFA (Sigma-Aldrich) to give a final concentration 1 mg/ml of emulsified chicken CII on day 0 and boosted with the same agent on day 21 and 42. Severity of disease was evaluated by visual inspection of the paws. Each paw was scored for the degree of inflammation on a scale from 0 to 4: 0, no evidence of erythema and swelling; 1, erythema and mild swelling confined to the midfoot (tarsals) or ankle joint; 2, erythema and mild swelling extending from ankle to the midfoot; 3, erythema and mild swelling extending from ankle to metatarsal joints; 4, erythema and severe swelling encompassing the ankle, foot, and digits. Scores from all four paws were added to give the total for each animal. The experiments were performed in accordance with the regulation of the Animal Care Committee of University of Washington.

Histopathological analyses. Experimental mice were euthanized by CO2 inhalation. Routine necropsy was performed, and the distal appendages were placed in 10% neutral-buffered formalin for 7 days. The tissue sections were processed for routine paraffin embedding, and hematoxylin and eosin staining following decalcification.

Measurement of anti-CII Ab’s. Anti-collagen Ab (IgM, IgG1, IgG2a) production was measured in the serum of mice either 14 days after the first immunization or at the end of the experiment (day 58) by ELISA. Briefly, serum samples from immunized mice were added in a threefold serial dilution on plates precoated with 10 ug/ml chicken CII. Collagen-specific Ab’s were detected with biotinylated goat anti-mouse IgM and rat antimouse IgG1 and IgG2a Ab’s (Southern Biotechnology Associates, Birmingham, Alabama, USA).

T cell cytokine measurement. Spleen cells from ICOS+/+ and ICOS−/− mice 14 days after the first immunization with chicken CII were either unstimulated or stimulated with 50 or 100 µg chicken CII, and cytokine production (IFN-γ, TNF-α, IL-4, and IL-17) in the 3-day culture supernatant was determined by ELISA (PharMingen, San Diego, California, USA). Proliferation was assayed after 3 days of treatment with different doses of chicken CII by adding 3H-thymidine to the culture for the last 8 hours. To further test the role of ICOS in costimulation of DBA/1 T cells, naive CD4+ T cells from lymph nodes and spleens of 6- to 8-week-old wild-type DBA/1 mice were isolated, as we reported previously (16). Purified naive CD4+ T cells were stimulat-
ed in triplicate with plate-bound anti-CD3 in the absence or presence of anti-ICOS. On day 4, Th cytokine production in the supernatant was measured by ELISA (PharMingen). To examine CD40L expression, lymph node cells from ICOS+/+ and ICOS–/– mice were activated with αCD3 (3 µg/ml) and then stained with a biotinylated αCD40L Ab, followed by streptavidin–R-phycoerythrin (Southern Biotechnology Associates) for flow-cytometry analysis.

Results
RA is an autoimmune disease affecting a large percentage of the human population. CD4+ T cells play crucial roles in the pathogenesis of the disease. How their function is regulated, however, is still poorly understood. In the current study, we examined the role of ICOS costimulatory receptor in CIA.

ICOS knockout mice are completely resistant to CIA. We analyzed the role of ICOS in RA using the murine CIA model. We backcrossed ICOS knockout mice six generations onto the DBA/1 background. ICOS–/– and ICOS+/+ DBA/1 mice were immunized at the base of the tail on day 0, 21, and 42 with CII in CFA. ICOS−/− mice developed severe joint inflammation as seen by others, evidenced by marked swelling and erythema of the hindpaws and forepaws (Figure 1a). Inflammation in these paws included the wrist and ankle and extended distally through the limb and digits (Figure 1b). In contrast, ICOS−/− DBA/1 mice were uniformly resistant to CIA (Figure 1a) and had no sign of paw or joint swelling (Figure 1b).

We further examined the experimental mice histologically. Only the ICOS−/− DBA/1 mice with clinical disease had histopathological lesions consistent with collagen-induced arthritis. We examined the pedal joints of ICOS−/− DBA/1 mice and ICOS+/+ DBA/1 mice (Figure 2). All of the ICOS−/− DBA/1 joints were histologically normal with no sign of tissue degeneration and inflammation. All of the ICOS−/+ DBA/1 mice had severe histopathological lesions characterized by extensive fibrovascular and proliferative synovitis composed of abundant fibroblasts, hypertrophic synoviocytes, and marked infiltration of inflammatory cells, primarily neutrophils and macrophages, lesser lymphocytes, and mast cells (Figure 2, b–f), which extended into the joint space. Additionally, in severely affected joints, there was moderate to severe cartilage destruction, and marked remodeling of bone. Often, the fibrovascular
proliferation and inflammation extended into the periarticular connective tissues and adjacent musculature. Reduced anti-CII humoral responses in the absence of ICOS.

To better characterize the immune mechanisms underlying CIA resistance by ICOS–/– mice, we measured first anti-collagen Ab production (IgM, IgG1, IgG2a) in the serum of mice at the end of the experiments (day 58) (Figure 3). CIA is best characterized by pathogenic anti-CII IgG, especially IgG2a Ab’s. Consistent with the resistance of ICOS–/– mice to CIA, we found they exhibited greatly reduced levels of IgG2a Ab to anti-CII. On the other hand, low levels of anti-CII IgG1 production were not severely affected in these mice (data not shown). Interestingly, anti-CII IgM was also reduced in the absence of ICOS.

ICOS has been shown previously by others and us to play an important role in regulating B cell Ig class switching (16–18, 20). We therefore examined if class-switching was affected in the absence of ICOS. Serum anti-CII Ab’s were measured from ICOS+/+ and ICOS–/– mice 14 days after the first immunization. At this time point, there was little anti-collagen IgG1 and IgG2a production by both groups (data not shown). On the other hand, IgM was produced most significantly by ICOS+/+ mice (Figure 3). Surprisingly, we found at this stage that ICOS–/– DBA/1 already exhibited greatly reduced anti-CII IgM in serum (Figure 3). This result suggests an important role of ICOS in the initial B cell response, which can result in IgG2a deficiency and CIA resistance by ICOS–/– mice.

T cell responses in the immunized ICOS–/– mice. We showed previously that ICOS is important for T cell activation and function (16). Defective B cell response in ICOS–/– could thus be caused by insufficient T cell priming or lack of certain T cell cytokine products. To analyze antigen-specific T cell responses in ICOS+/+ and ICOS–/– mice, we immunized ICOS+/+ and ICOS–/– with CII, and their spleen cells harvested 14 days later were restimulated with different doses of CII. T cell proliferation and cytokine secretion were examined. ICOS+/+ cells exhibited moderately reduced T cell proliferation, suggestive of a minor role of ICOS in T cell priming in vivo (Figure 4a).

Since the marginally reduced T cell priming described above could not fully explain the complete resistance of ICOS–/– mice to CIA, we further examined IFN-γ, TNF-α, IL-4, and IL-17 production by spleen cells in response to CII (Figure 4b). No IL-4 could be detected by either ICOS+/+ or ICOS–/– cells, correlating with the notion that the CIA protocol generates a Th1 response in vivo. No difference was observed in expression of IFN-γ in ICOS–/– and ICOS+/+ mice. Normal IFN-γ production by ICOS–/– mice would also argue against a role of ICOS in regulating Ig class switching to IgG2a. In addition, TNF-α, an important cytokine for RA, was found to be produced normally in the absence of ICOS. Therefore, a TNF-α–independent mechanism must confer CIA resistance in the knock-
out mice, suggesting that an anti-ICOS therapy for RA may serve as an alternative for patients who fail TNF-α-targeted therapy.

**ICOS regulates IL-17 expression.** Interestingly, spleen cells from ICOS−/− mice produced a remarkably decreased amount of IL-17 in response to CII (Figure 4b). IL-17 is a new cytokine secreted by CD4+ activated memory T cells and is frequently found in RA synovium (8, 21, 22). The cellular responses to IL-17 are similar to IL-1, including IL-6, IL-8, G-CSF, and prostaglandin E2 (PGE2) production (8, 21). The effect of IL-17 on cartilage was associated with its destruction, including activation of NO, and IL-17 has also been described as a potent stimulator of osteoclastic bone reabsorption due to PGE2 synthesis (23–25). IL-17 produced by CD4+ cells in the joint tissue may contribute to the inflammatory process involved in RA. In support of this notion, overexpression of IL-17 in the joints resulted in inflammatory infiltration of the synovium and aggressive cartilage degradation (26). Blockade of IL-17 action with a soluble receptor significantly reduced the CIA, including a clear suppression of joint damage (27). Thus, defective IL-17 production in the ICOS−/− mice may contribute to lack of joint inflammation in these mice. Since ICOS ligand, B7H, is expressed in inflamed tissues, ICOS-B7H interaction may regulate IL-17 local expression in the joint tissue in the CIA model and mediate the inflammatory responses. On the other hand, a recent study of the IL-17 knockout mice indicates a novel role for IL-17 in humoral immune responses (28). Although the role of IL-17 in autoimmune production in the CIA model has not been formally addressed, the reduced anti-CII autoantibodies in ICOS−/− mice possibly could be attributed to the IL-17 deficiency.

IL-17 has emerged as an important T cell–derived cytokine in many aspects of immune responses; however, how it is regulated is very poorly understood. Our result indicates a novel role of ICOS in IL-17 expression in vivo. To further examine ICOS regulation of IL-17 expression, we tested the ability of ICOS costimulation to induce this cytokine production by naive T cells. C398-4A is a mAb against ICOS (29, 30); its specificity was further confirmed by us previously based on its lack of binding to ICOS−/− cells (16). We stimulated naive Th cells from DBA/1 mice with different combinations of anti-CD3, CD28, and ICOS. CD28 costimulation greatly increased IFN-γ but not IL-17 expression. Since ICOS upregulation on activated T cells requires CD28 costimulation (31), we used a combination of anti-CD3, CD28, and ICOS to examine ICOS effect. We did not find any enhancement of IFN-γ production by this treatment as compared with cells treated only with anti-CD3 and CD28 (Figure 5a). On the other hand, ICOS costimulation significantly increased IL-17 production by activated T cells. This result indicates a unique regulatory role for ICOS in IL-17 expression by activated T cells.

ICOS has been implicated previously in regulating CD40L expression by activated T cells (17). In addition to T cell cytokines, we also examined the CD40L expression. ICOS+/+ and ICOS−/− lymph node cells were activated with anti-CD3 for 6 hours, and cell-surface CD40L expression was examined by flow cytometry. Consistent with our previous report (16), ICOS−/− cells expressed CD40L at the same level as the ICOS+/+ cells. Therefore, it is unlikely that ICOS regulates CIA response through a CD40L-dependent mechanism.

In conclusion, we found ICOS−/− mice on DBA1 background to be completely resistant to CIA. ICOS−/− mice exhibited reduced B cell response in anti-CII Ab production. In addition, we report a novel role of ICOS in regulation of IL-17 expression. Since IL-17 has been shown to mediate joint tissue inflammation and is important in humoral immune responses, ICOS thus possibly mediates autoimmune arthritis by regulating IL-17 expression. Considering that ICOS is only expressed on activated T cells, anti-ICOS approaches may therefore provide specific T cell–based therapy for RA patients.

**Acknowledgments**

We thank Charlene Carr-May for her histotechnological assistance, Durbaka V. R. Prasad for his assistance in experimental procedures, and the entire Dong lab for their help and discussion. This work is supported in part by a start-up fund from the Department of Immunology at the University of Washington. Richard Flavell is an investigator for the Howard Hughes Medical Institute, and Chen Dong is an Arthritis Investigator award recipient from the Arthritis Foundation.

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