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IL-33 Exacerbates Autoantibody-Induced Arthritis

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Rheumatoid arthritis pathogenesis comprises dysregulation in both innate and adaptive immunity. There is therefore intense interest in the factors that integrate these immunologic pathways in rheumatoid arthritis. In this paper, we report that IL-33, a novel member of the IL-1 family, can exacerbate anti–glucose-6-phosphate isomerase autoantibody-induced arthritis (AIA). Mice lacking ST2 (ST2−/−), the IL-33 receptor α-chain, developed attenuated AIA and reduced expression of articular proinflammatory cytokines. Conversely, treatment of wild-type mice with rIL-33 significantly exacerbated AIA and markedly enhanced proinflammatory cytokine production. However, IL-33 failed to increase the severity of the disease in mast cell-deficient or ST2−/− mice. Furthermore, mast cells from wild-type, but not ST2−/−, mice restored the ability of ST2−/− recipients to mount an IL-33–mediated exacerbation of AIA. IL-33 also enhanced autoantibody-mediated mast cell degranulation in vitro and in synovial tissue in vivo. Together these results demonstrate that IL-33 can enhance autoantibody-mediated articular inflammation via promoting mast cell degranulation and proinflammatory cytokine production. Because IL-33 is derived predominantly from synovial fibroblasts, this finding provides a novel mechanism whereby a host tissue-derived cytokine can regulate effector adaptive immune response via enhancing innate cellular activation in inflammatory arthritis.

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Materials and Methods

Mice

BALB/c mice were obtained from Harlan UK (Bicestor, U.K.). ST2−/− BALB/c mice were generated as described previously (35). Mast cell-deficient Kit−/−/Wsh mice in a C57Bl/6 background were from The Jackson

Abbreviations used in this paper: AIA, autoantibody-induced arthritis; BMMC, bone marrow-derived mast cell; DLN, draining lymph node; RA, rheumatoid arthritis; WT, wild-type.

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Laboratory (Bar Harbor, ME). All of the mice were used at 8- to 10-wk-old and maintained at the Biological Services Unit, University of Glasgow. All of the animal experiments were carried out in accordance with the Home Office, U.K., guidelines.

Mouse IL-33 was produced as described previously (33). Endotoxin levels were <0.1 EU/μg of protein according to the Limulus amoebocyte lysate QCL-1000 pyrogen test (Lonza, Basel, Switzerland).

**Generation of mouse bone marrow-derived mast cells**

Bone marrow–derived mast cells (BMMC) were derived from female BALB/c mice and maintained as described previously (33, 36). Briefly, bone marrow cells from femurs of mice were cultured with 10 ng/ml IL-3 and 20 ng/ml stem cell factor in complete RPMI medium (RPMI 1640 supplemented with 10% FCS, 2 mM l-glutamine, and 100 U/ml of penicillin and streptomycin) in a 5% CO2 atmosphere. After 6 wk, BMMCs were collected and tested for c-Kit, FcεRI, and ST2 expression by flow cytometry using anti-c-Kit (BD Biosciences, San Jose, CA), anti-FcεRI (eBioscience, Hatfield, U.K.), and anti-ST2 (R&D Systems, Minneapolis, MN) Abs. For in vitro activation, BMMCs (×10^5 cells/ml) were preincubated with K/BxN or normal mouse serum overnight then stimulated with or without IL-33 for different times. β-Hexosaminidase released (45 min) in the culture supernatant was measured by the method described previously and represented as the percentage of the total enzyme (37). The levels of TNF-α, IL-1β, IL-3, IL-4, IL-5, IL-6, IL-10, IL-12, IL-13, IFN-γ, MCP1, MCP3, and MIP1α in the supernatant (48 h) were determined by Luminex (Cytokine 20-Plex; BioSource, London, U.K.) following the manufacturer’s instructions. For in vivo engraftment, ST2^-/- mice were injected i.v with BMMCs (×10^5 cells per mouse, the BMMCs contained 90% c-Kit^+ FcεRI^+ mast cells) as described previously (33). Four weeks later, AIA was induced in the mice.

**Induction of AIA and assessment of arthritis**

AIA was induced in mice by the injection of anti–glucose-6-phosphate isomerase Ab (IgG1) containing sera from K/BxN transgenic mice as described previously (7). Briefly, 6- to 8-wk-old WT or ST2^-/- mice (six mice per group) were injected with 50 or 100 μl K/BxN serum. To investigate the effect of IL-33 in AIA, mice received daily i.p. injections of IL-33 (0.1 μg per mouse) from days 0 to 4. Control mice received the same volume (100 μl) of PBS. All of the mice were monitored daily for signs of arthritis (7). Ankle and paw thickness were measured with a dial caliper (Kroeplin, Munich, Germany). Scores were assigned based on erythema, swelling or loss of function present in each paw on a scale of 0–3, giving a maximum score of 12 per mouse (32, 33).

**Quantitative PCR**

This was carried out as described previously (38. 39). Briefly, total RNA was extracted from joint tissue or draining lymph nodes (DLNs) using the TRIzol method (Invitrogen, Carlsbad, CA) and purified further with RNeasy columns (Qiagen, Valencia, CA). Real-time PCR was performed using the specific probe and primers from Applied Biosystems (Foster City, CA) (28).

**Measurement of cytokines and serum Ab levels**

All of the cytokine concentrations in serum and culture supernatant of DLN or spleen cells were detected by Luminex following the manufacturer’s instructions. The Ab titres of individual sera were determined by ELISA (BD Pharmingen, San Diego, CA).

**Histological examination**

For histological assessment, AIA and control mice were sacrificed at the end of the experiments, and the hind limbs were removed, fixed in 10% neutral-buffered formalin, and decalcified. Sections (4 μm) were stained with H&E. The joint pathology was examined and scored as described previously (32, 33). The sections were scanned with a Duoscan T2000XL microscope (Agfa-Gevaert N.V., Mortsel, Belgium), and pictures were taken with a Fuji X digital camera (HC-300Z; Fujifilm, Tokyo, Japan) at ×40 magnification. The paraffin sections also were stained with toluidine blue for mast cells and examined with a microscope (BX 51; Olympus, Melville, NY) using ×10, ×40, and ×100 UplanApo lenses. Mast cell numbers in the joints were calculated by counting the cells under light microscopy in six different sections derived from six mice. The percentage of degranulated mast cells in the joint was calculated by counting the number of cells with >10% extrusion of granules as described previously (36). Immunohistochemical staining of IL-33 was performed using anti-IL-33 and control Abs (R&D Systems) as described previously (30, 33).

**Statistical analysis**

Clinical scores were analyzed using the nonparametric Mann-Whitney U test, and histological scores were analyzed by one-way ANOVA test. Differences between cumulative incidences at a given time point were analyzed by the χ^2 contingency analysis. Cytokine and IgG levels were compared using the Student t test.

**Results**

**ST2^-/- mice develop impaired AIA**

To examine the role of ST2 in AIA, groups of sex- and age-matched WT BALB/c and ST2^-/- BALB/c mice were injected i.p. with anti–glucose-6-phosphate isomerase Ab containing K/BxN serum, and arthritis development was monitored daily for 3 d. At the end of the experiment, mice were sacrificed, and serum, DLNs, and joint tissues were harvested. DLN cells were cultured with anti-CD3 Ab for 3 d, and the culture supernatant was analyzed for cytokines by ELISA. Cytokine mRNA expression in the joints was measured by quantitative PCR. Cytokine and IgG concentrations in the serum were determined by ELISA. WT mice developed AIA within 24 h after K/BxN serum injection. ST2^-/- mice showed significantly reduced AIA in all of the clinical parameters measured compared with those of the WT mice (Fig. 1A). The levels of TNF-α message in the joints were reduced significantly in ST2^-/- mice compared with those in WT AIA mice (Fig. 1B). The IFN-γ and IL-17 levels remained lower in ST2^-/- mice than in WT mice (Fig. 1C).
unchanged (Fig. 1B and data not shown). No significant differences in the levels of the inflammatory cytokines IL-1β, TNF-α, and IFN-γ in the serum and DLNs between WT and ST2^{−/−} mice were detected (data not shown). ST2^{−/−} AIA mice showed significantly reduced levels of serum IgG2a and IgG1 compared with those of WT mice (Fig. 1C). These results show that IL-33/ST2 signaling is associated closely with the disease development in AIA.

**IL-33 exacerbates AIA**

We next directly tested the arthritic role of IL-33 in AIA. To see a maximal disease-exacerbating effect of injected IL-33, AIA was induced in WT and ST2^{−/−} mice on day 0 with a suboptimal dose of K/BxN serum (50 μl), and then mice were injected with IL-33 (0.1 μg per mouse) or PBS i.p. daily for 5 d. IL-33–treated mice developed significantly exacerbated AIA compared with that of the control PBS-treated mice (Fig. 2A). IL-33 injection did not have a significant effect on the severity of AIA in ST2^{−/−} mice (Fig. 2B). IL-33 treatment alone without K/BxN serum did not induce inflammatory arthritis (data not shown). IL-33 administration markedly increased the mRNA levels of the proinflammatory cytokines IL-1β and TNF-α, but not IFN-γ and IL-17, in the joints of WT mice (Fig. 2C and data not shown). IL-33 administration also induced higher concentrations of serum IgG1 and IgG2a than those in PBS control mice (Fig. 2D). Histological analysis shows that the IL-33 treatment markedly increased mononuclear and polymorphonuclear cell infiltration into the joints, with significant synovial hyperplasia and adjacent cartilage and bone erosion in the AIA mice (Fig. 2E). Furthermore, we determined IL-33 expression in the joint tissues of normal and AIA mice by immunohistochemical staining. We found that IL-33 proteins were detected specifically in the inflamed joints of AIA mice but not in normal joints (Fig. 2F). The levels of IL-33 were enhanced markedly in the joints of mice treated with the K/BxN serum together with IL-33 (Fig. 2F). Moreover, mast cells were also clearly present in the joint tissue, and the mast cells were located among the IL-33-positive cells in the inflamed joints.

Together these data clearly indicate that IL-33 potentiates autoantibody-elicited clinical severity of AIA, local proinflammatory cytokine production, and articular damage.

**IL-33 exacerbates AIA mainly via mast cells**

We next identified the cellular target of IL-33 in the context of AIA. Because mast cells express membrane ST2 at a high density and are able to directly respond to IL-33 (33, 40–43) and mast cell-deficient Kit^{W−/−} mice are completely resistant to AIA (7), we sought to investigate the role of mast cells in IL-33–enhanced AIA. We first

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**FIGURE 2.** IL-33 exacerbates AIA in WT but not ST2^{−/−} mice. WT (A) and ST2^{−/−} (B) mice were injected i.p. with 50 μl K/BxN serum and then injected i.p. with IL-33 (0.1 μg per mouse) or PBS daily from day 0–5. Mice were monitored for disease progression as in Fig. 1. C, Mice were sacrificed on day 5, and cytokine mRNA expression levels in DLN cells and joint tissues were determined by quantitative PCR. D, The concentrations of serum Ab in individual samples (n = 10) were determined by ELISA. E, The paws were removed, sectioned, and stained with H&E. F, IL-33 protein (stained brown) levels in the normal and inflamed joint tissue were determined by immunohistochemical staining. Arrows indicate mast cells. The pathogenic score was determined as described in Materials and Methods. Data are mean ± SEM. *p < 0.05, compared with controls in all of the figures as indicated (n = 5). Data are representative of at least two experiments.
determined the arthritogenic role of IL-33 in AIA in the mast cell-deficient KitW/wsh mice. AIA was induced in WT and mast cell-deficient mice, and mice were inoculated with PBS or IL-33 as previously. As expected, WT mice developed AIA, which was exacerbated further by IL-33 treatment (Fig. 3A). Unexpectedly, and in contrast to the KitW/wsh mice, KitW/wsh mice also developed detectable arthritis when injected with the K/BxN serum, although the disease was significantly milder than that in the WT mice (Fig. 3A). However, IL-33 failed to increase AIA in the KitW/wsh mice (Fig. 3A). These results therefore show that the IL-33–mediated exacerbation of AIA is associated with mast cell activities.

We further confirmed the importance of mast cells in IL-33–enhanced AIA by a mast cell reconstitution experiment. BMMCs were generated in vitro as reported previously (33, 36). Groups of ST2−/− mice were generated in vitro as reported previously (33, 36). Groups of ST2−/− mice were engrafted i.v. with BMMCs from WT or ST2−/− mice of the same BALB/c background. Four weeks later, AIA was induced in the mice, and IL-33 was administered as described in Fig. 2A. A group of WT positive control mice also was induced and for AIA and injected with IL-33 as the ST2−/− recipients. WT mice treated with IL-33 developed significant AIA, whereas ST2−/− mice engrafted with ST2−/− BMMCs and treated with IL-33 developed minimal AIA (Fig. 3B). Importantly, WT BMMCs partially, but significantly, restored the disease severity of AIA in ST2−/− mice following IL-33 administration (Fig. 3B). Because the only cells in the ST2−/− recipients capable of responding to IL-33 were the engrafted WT BMMCs, these data therefore confirm that mast cells are associated with the increased severity mediated by IL-33 in AIA.

**IL-33 promotes mast cell degranulation in the joints of AIA mice**

We then determined whether IL-33 exacerbates AIA via its ability to enhance autoantibody-mediated mast cell degranulation. AIA was induced in ST2−/− and WT mice, and mice were injected with IL-33 or PBS as previously. The inflamed ankle joints were removed at day 4, fixed, and sectioned. The mast cells in the joint tissues were identified by toluidine blue staining, and the intact and degranulated mast cells were quantified as described previously (36). Consistent with a previous report (7), K/BxN serum injection caused ∼37.5% of mast cells to degranulate in the joints of WT mice (Fig. 4A, 4E). The number of degranulated mast cells in the ST2−/− mice injected with...
K/BxN serum was significantly lower (22.5%, \( p < 0.05 \)) (Fig. 4B, 4E). IL-33 injection resulted in 55% of mast cell degranulation in WT mice (Fig. 4C, 4E), whereas IL-33 treatment did not enhance mast cell degranulation in ST2^{-/-} mice (Fig. 4D, 4E). IL-33 alone failed to trigger mast cell degranulation in naive mice without autoantibody injection (data not shown). Thus, IL-33 enhances Ab-mediated mast cell degranulation in AIA, which also may contribute to the pathogenesis of AIA.

To demonstrate the synergistic effect of IL-33 and autoantibodies in the activation of mast cell degranulation, we preactivated BMMCs with K/BxN or normal mouse serum overnight and then stimulated the cells with or without IL-33 for different times. The levels of \( \beta \)-hexosaminidase and cytokines or chemokines in the culture supernatants were determined. Although IL-33 alone activated modest levels of \( \beta \)-hexosaminidase and cytokine or chemokine production by mast cells, these levels were markedly enhanced by the presence of the K/BxN serum but not by normal mouse serum (Fig. 5). Our result therefore demonstrated that IL-33 is involved directly in mast cell activities and both IL-33 and autoantibodies are necessary for a maximal induction of mast cell degranulation and proinflammatory mediator production.

Discussion

The mechanisms promoting the induction and function of autoantibodies in autoimmune diseases such as RA remain unclear. Data presented here demonstrate for the first time that IL-33 is required for the full induction and exacerbation of the clinical onset of AIA. Because AIA is an autoantibody-triggered, innate cell-mediated arthritic condition, our results provide a novel arthritogenic pathway for IL-33 in inflammatory arthritis.

Our result from Kit^{-/-} mice suggests that mast cells are important but not essential for the development of AIA (Fig. 3A). This is distinct from a previous report showing that mast cell-deficient Kit^{-/-} mice are completely resistant to AIA induction (7). The reason for this discrepancy is unclear but may be due to the different abnormalities of other cell lineages, in particular the neutrophils, in these mice. It is known that mast cell-deficient Kit^{-/-} mice also lack neutrophils (44, 45). In contrast, the Kit^{-/-} strain has normal neutrophil numbers and phenotype (44, 45). Because neutrophils also are involved critically in the pathogenesis of AIA (45–47), the complete AIA resistance in Kit^{-/-} mice may be due to their deficiency in both mast cells and neutrophils. Zhou et al. (45) reported that Kit^{-/-} mice developed arthritis indistinguishable from that in the WT mice when the mice were injected with anti-collagen Ab together with LPS. Because LPS is a strong neutrophil activator, these results are consistent with the notion that both mast cells and neutrophils are important for the manifestation of Ab-mediated arthritis. Nevertheless, the clinical parameters of AIA in Kit^{-/-} mice could not be further enhanced by IL-33, and IL-33 specifically exacerbated AIA in ST2^{-/-} mice repopulated with WT but not ST2^{-/-} mast cells. These results therefore demonstrated that mast cells are the main cellular target for IL-33 in enhancing AIA.

Our results suggest that IL-33 may amplify AIA by at least three mechanisms: First, IL-33 is involved critically in the maturation and function of mast cells (38, 39). Therefore, IL-33 likely worsens AIA by accelerating mast cell maturation and activation. Second, IgG-triggered mast cell degranulation and associated inflammatory mediator release are correlated with the severity of inflammatory arthritis (7). Thus, IL-33 also may exacerbate AIA by promoting mast cell degranulation in the joints. Because IL-33 alone fails to induce AIA or mast cell degranulation in vivo, IL-33 may do so by potentiating autoantibody-mediated mast cell activation. This is in agreement with early reports that IL-33 is unable to directly trigger mast cell degranulation in vitro (41–43). Third, we found that IL-33 signals drive the expression of articular proinflammatory cytokines (IL-1\( \beta \) and TNF-\( \alpha \)), which also are required for the initiation of AIA (38, 39). IL-33 also can enhance proinflammatory cytokine production by IgG-primed mast cells.

**FIGURE 5.** IL-33 directly promotes autoantibody-initiated mast cell degranulation and proinflammatory mediator production in vitro. Mast cells were precultured overnight with K/BxN serum or normal mouse serum and then stimulated with or without IL-33 (2 ng/ml). A, \( \beta \)-Hexosaminidase release was detected 45 min after the culture. B, For cytokine and chemokine production, the cells were cultured for 48 h, and cytokine and chemokine concentrations in the supernatant were determined by Luminex. Data are mean \( \pm \) SD. \( *p < 0.05 \) and \( **p < 0.01 \), compared with controls by Student \( t \) test. Data are representative of two experiments.
We have reported recently that IL-33 is also capable of promoting IgE-mediated mast cell degranulation and enhancing anaphylaxis by activating the phospholipase D1 and sphingosine kinase 1 pathway. It will be intriguing to know whether IL-33 uses the same or different mechanisms to promote IgG-mediated mast cell activation and degranulation in AIA. We observed that IL-33 signals also are able to promote IgG1 and IgE2a production in AIA. This is consistent with our previous report that IL-33 signals drive Ag-specific IgG2a and IgG1 in collagen-induced arthritis (33). Although the Ag specificity and the precise role of these Abs in AIA is still unknown, our results nevertheless demonstrated that IL-33 is a powerful Ab inducer leading to arthritic pathology. Our results also suggest that IL-33 may promote humoral arthritis by inducing autoantibody production and subsequently potentiating Ab-mediated arthritis reactions.

Together, our data demonstrate that IL-33 is an innate cell-derived arthritogenic factor that is able to drive both cellular and humoral arthritis responses. This finding provides an intriguing mechanism whereby host tissue articular cells of the fibroblast lineage can regulate and promote humoral and innate immune activation to the detriment of joint structure and homeostasis. As such, it offers novel therapeutic potential.

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Disclosures

The authors have no financial conflicts of interest.

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