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Inhibitory Fcγ Receptor Is Required for the Maintenance of Tolerance through Distinct Mechanisms

Fubin Li,*,† Patrick Smith, † and Jeffrey V. Ravetch†

The inhibitory FcγR FcγRIIB is widely expressed on B cells, dendritic cells (DCs), and myeloid effector cells and modulates a variety of Ab-driven in vivo functions. Although it has been established that FcγRIIB plays an important role in the maintenance of peripheral tolerance, the responsible cell-specific FcγRIIB expression remains to be determined. In this study, we generated mice with selective deletion of FcγRIIB in B cells, DCs, and myeloid effector cells and evaluated these novel strains in models of tolerance and autoimmune diseases. Our results demonstrate that mice with selective deletion of FcγRIIB expression in B cells and DCs have increased Ab and T cell responses, respectively, and display enhanced susceptibility to disease in distinct models, suggesting that FcγRIIB expression in distinct cellular populations contributes to the maintenance of peripheral tolerance through different mechanisms. The Journal of Immunology, 2014, 192: 000–000.

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Abbreviations used in this article: alum, aluminum hydroxide; ANA, anti-nuclear Ab; bCIA, bovine type II collagen-induced arthritis; cCIA, chicken type II collagen-induced arthritis; CGG, chicken γ globulin; CIA, collagen-induced arthritis; DC, dendritic cell; EC, extracellular; ES, embryonic stem; GC, germinal center; neo, neomycin-resistant gene; TMB, tetramethylbenzidine; WT, wild-type.

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was the observation that hematopoietic stem cells derived from patients homozygous for the I232T polymorphism, when transplanted into immunodeficient recipient mice, resulted in reconstituted immune systems that failed to maintain tolerance and developed anti-DNA Abs (21).

Therefore, defects in FcγRIIB function and regulation have emerged as a common feature of lupus and other autoimmune diseases, contributing both to disease susceptibility and progression. However, the relative contributions of FcγRIIB expression in different cellular compartments, such as B cells, DCs, and myeloid effector cells, to these phenotypes have not been firmly established. In the current study, we have investigated the contributions of FcγRIIB expression in B cells, DCs, and myeloid effector cells to the maintenance of peripheral tolerance through the analysis of mice conditionally deleted for this receptor in these immune cells.

Materials and Methods

Generation of mice carrying Fcgr2b<sup>−/−</sup> and Fcgr2b<sup>Δ</sup> alleles

To generate Fcgr2b germline and conditional knockout mice from B6 ES cells, two homologous arms cloned from the Fcgr2b locus of C57BL/6 genomic DNA were inserted into an ES cell–targeting vector (Supplemental Fig. 1). The 5′ homologous arm, a 8.5-kb DNA fragment containing the exons coding for the S2, extracellular (EC1), EC2, and transmembrane domains of FcγRIIB, was generated by PCR (Expand Long Template PCR; Roche) using primers 5′-CCCCATCGATAGACAGAAATGGTTCCCTGAAAGGTCACT-3′ and 5′-ATATCTTGCGGCGGCTTTTGAGCACTGTTAAGAATGGG-3′ and cloned into the ClaI/NotI sites of the pEasyFlox vector. A loxP-neo-loxP cassette encoding neomycin-resistant gene (neo) was inserted after this 8.5-kb fragment in the NotI/Sall sites of pEasyFlox, and its location in respect to the gene would place it 1300 bp downstream of the transmembrane exon (exon 5) in intron 5. The 3′ homologous arm of the targeting vector, a 4.3-kb DNA fragment containing the exons coding for the three intracellular domains IC1, IC2, and IC3, was generated by PCR (Expand Long Template PCR; Roche) using primers CCGCGTGCAACAACATGTGGGCGCCCTACAGGAATA-3′ and 5′-ATAGCTCTGAGTCTCTCTCTTTACTACTGTCACAGC-3′ and cloned into the Sall/Xhol sites of pEasyFlox. The third loxP site was inserted in the HindIII site in the 5′ homologous arm, 134 bp upstream to the EC1 exon. Transfection of B6 ES cells with the targeting vector and the subsequent selection and screening were performed in The Rockefeller University Gene Targeting Facility. Clones containing the targeted Fcgr2b allele (Fcgr2b<sup>fl/fl</sup>) were identified by Southern blot analysis of EcoRV-digested genomic DNA with a probe that hybridizes outside of the targeting vector. Based on the design of the targeting vector, a hybridized band of 13.6 kb would identify the WT Fcgr2b allele, and a band of 10.5 kb would identify the targeted Fcgr2b<sup>loxP</sup> allele (Supplemental Figs. 1A, 1B). Positive clones that also contain the Neo<sup>+</sup> site inserted in the HindIII site in the 5′ homologous arm (confirmed by PCR and sequencing [Roche]) were selected for microinjection into C57BL/6 embryos, and chimeric male offspring bred to C57BL/6 females treated with 100 μg NP-chicken γ globulin (CGG) in aluminum hydroxide (alum) and analyzed 12 d later. Splenic single-cell suspensions depleted for erythrocytes were stained with fluorescent-conjugated anti-B220 (RA3-6B2), anti-Fas (Jo2), anti-IgG1 (A85-1), and anti-FcγRIIB/III (2.4G2). To analyze FcγRIIB levels in thyoglicolate-elicited macrophages, mice were i.p. injected with 2 ml thioglycollate. Seven days later, peritoneal cavity cells were harvested by gently flushing with cold PBS and stained with fluorescent-conjugated F4/80 (BM8), CD11b (M1/70), and anti-FcγRIIB (L7.12.7). Abs. Macrophages were defined as CD11b<sup>+</sup>F4/80<sup>+</sup> cells.

Ab response

Mice were immunized i.p. with 100 μg NP<sub>P3</sub>-CGG emulsified in CFA on day 0 and boosted with 100 μg NP<sub>P3</sub>-CGG emulsified in IFA on day 28. Levels of NP-specific IgG on days 0, 14, and 28 were determined by ELISA. Serum samples from these mice were used for the analysis of IgG levels, and 1:5000 diluted HRP-conjugated goat anti-mouse IgG (Bethyl Laboratories) were used as capture Abs, and IgG was detected by HRP-conjugated goat anti-mouse IgG (Jackson ImmunoResearch Laboratories) and tetramethylbenzidine (TMB) substrates.

Analysis of autoimmune phenotypes

Mice were monitored for survival for 10 mo. Proteinuria levels were monitored using Chemstrip 2 GP strips (Roche) monthly, and mice with proteinuria levels ≥100 mg/dl were considered sick. Defective levels of anti-nuclear Abs (ANA) of IgG class, 1:200 diluted serum samples were applied to REAADS ANA Test plates (Corgenix), incubated at room temperature for 1 h, and washed five times with PBS with 0.05% Tween-20. IgG Abs were detected with HRP-conjugated goat anti-mouse IgG-Fc (1:5000; Jackson ImmunoResearch Laboratories) and TMB substrate. To analyze the levels of total IgG<sub>M</sub> or IgG<sub>A</sub> in total serum, 1:100 diluted serum samples were used for the analysis of IgM levels, 1:1,000,000 diluted serum samples were used for the analysis of IgG levels, and 1:5000 diluted HRP-conjugated goat anti-mouse IgM (Southern Biotechnology Associates) or IgG-Fc Abs (Jackson ImmunoResearch Laboratories) plus TMB substrates were used to detect IgM or IgG, respectively. Immune complex precipitation from fluorescence staining of FcγR<sub>IIa</sub> cells (Hep-2 cells) was performed following the manufacturer’s instructions. Diluted serum samples (1:100) collected from 8- to 9-mo-old mice were analyzed. IgG Abs were detected using FITC-conjugated goat anti-mouse IgG-Fc (1:200; Jackson ImmunoResearch Laboratories). CIA experiments were performed as described (28). Briefly, mice were immunized intradermally with 100 μg bovine or chicken type II collagen emulsified in adjuvant (IFA with 4 mg/ml Mycobacterium tuberculosis H37 Ra) to induce arthritis. Arthritis incidences were monitored weekly for 11 wk. To analyze mouse collagen-specific IgG response, serum samples were diluted 5000-fold and analyzed with a mouse IgG<sub>A</sub> anti-mouse collagen type II ELISA kit (MB Diagnostics).

K/BxN arthritis model

Experiments using the K/BxN arthritis model were performed as described previously (29). Mice were injected with 200 μl K/BxN sera i.e. and monitored for the development of arthritis for a period of 12 wk. Mice (0–12) were assigned to each paw of individual mice depending on the severity of arthritis, and the summed scores of four paws of individual mice (0–12) were recorded as their arthritis clinical scores.
OT-I T cell expansion

OT-I T cell expansion experiments were performed using a modified protocol (30). Briefly, on day −1, 2 million CFSE-labeled CD45.1+ OT-I T cells enriched by MACS-negative selection were adoptively transferred through i.v. injection into WT, Fcgr2b−/−, or Fcgr2b conditional knockout mice with CD11cCre. On day 0, each mouse received 150 μg rabbit anti-OVA IgG through i.v. injection, followed by 2.5 μg OVA 4 h later. The concentration of CD45.1+CD8+Vα2+ cells in blood was analyzed 3 d later by FACS.

Statistics

All statistical analyses were performed in Prism 5 for Windows (version 5.04; GraphPad), one-way ANOVA with Dunnett post hoc test was used in Figs. 2, 4A, and 7 to compare all groups to the WT or Fcgr2bfl/fl control group, one-way ANOVA with Tukey post hoc test was used in Fig. 3 and Supplemental Fig. 3, and χ2 test was used in Figs. 4B, 5, and 6B and Supplemental Fig. 2 to compare every group to the Fcgr2bfl/fl control group.

Results

Generation of Fcgr2b germline and conditional knockout mice from B6 ES cells

Fcgr2b germline and conditional knockout mice were generated by crossing a mouse strain with loxP-flanked Fcgr2b alleles (Fcgr2bfl/fl) derived from B6 ES cells (Supplemental Fig. 1) to CagCre (22), Mb1Cre (23), Cg1Cre (24), CD11cCre (25), and LysMCre (26) B6 mice. Mb1Cre is expressed in all B cells, whereas Cg1Cre expression is restricted to GC and post-GC B cells. CD11cCre is primarily expressed in DCs, and LysMCre is expressed in most myeloid effector cells. As shown in Fig. 1A, homozygous Fcgr2bfl/fl mice have equivalent FcyRIIIB expression as WT C57BL/6 mice, confirming that the inserted loxP sites in the Fcgr2bfl/fl allele have no effect on the expression of FcyRIIIB. Mb1Cre/Fcgr2bfl/fl mediated specific and efficient deletion of Fcgr2b in all B cells examined; in contrast, Cg1Cre/Fcgr2bfl/fl did not delete Fcgr2b in resting B cells. To determine which B cell populations delete Fcgr2b in Cg1Cre/Fcgr2bfl/fl mice, Fcgr2bfl/fl mice with Cg1Cre were immunized with NP-CGG in alum and examined for FcyRIIIB expression in IgG1+ and IgG1− GC B cells, as defined by B220+Fas−IgG1+ and B220+Fas+IgG1− cells, respectively. As shown in Fig. 1B, FcyRIIIB expression was reduced in the majority of both IgG1+ and IgG1− GC B cell subsets, consistent with previous studies showing that Cg1Cre expression is restricted to GC and post-GC B cells (24). CD11cCre/Fcgr2bfl/fl mediated efficient deletion of Fcgr2b in DCs (CD11c+), as well as in some monocytes (CD11c+). LysMCre/Fcgr2bfl/fl-mediated

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

Expression profiles of FcyRIIIB in WT and mutant mice with germline or conditional knockout of Fcgr2b. (A) Histogram profiles showing the expression of FcyRIIIB in the indicated cell types of the indicated mice. FcyRIIIB levels were analyzed in B cells (CD19+), monocytes (CD11b+Gr1low/2 SSChigh), and neutrophils (CD11b+NK1.1highSSChi/2) in the peripheral blood and DCs (CD11chigh) in the spleen in WT C57BL/6 mice and mice with germline or conditional knockout of Fcgr2b. (B) The gating strategy for non-GC B cells and IgG1+ and IgG1− GC B cells and histogram profiles showing Cg1Cre-mediated deletion of Fcgr2b in these cells. Mice with the indicated genotypes were treated with NP-CGG in alum and analyzed 12 d later for the expression of FcyRIIIB in splenic non-GC B cells (B220−Fas+) and IgG1+ and IgG1− GC B cells (B220−Fas−IgG1+ and B220−Fas−IgG1−, respectively). (C) Histogram profiles showing FcyRIIIB levels in thioglycollate-elicited macrophages (CD11b+F4/80+) isolated from mice of the indicated genotypes. Representative of two independent experiments with three mice per group.
deletion of Fcgr2b was detectable in monocyte and thiglycollate-elicited macrophages (Fig. 1A, 1C), but not in B cells or DCs. However, the deletion efficiency of LysMCre was estimated to be only 20–60%, as has been reported previously for some other genetic systems (31, 32). These data indicate that we have generated B6 mice with a conditional knockout of Fcgr2b in B cells (Mb1Cre), GC, and post-GC B cells (Cg1Cre), DCs and some monocytes (CD11cCre), and monocytes and macrophages (LysMCre).

*FcyRIIB contributes to tolerance through distinct mechanisms*

To determine the effect of germline and conditional knockouts of Fcgr2b in different immune cells on the primary and secondary thymic-dependent Ab response, levels of NP-specific IgG were analyzed in mice immunized and boosted with the model Ag NP-CGG. As shown in Fig. 2, WT (Fcgr2b<sup>fl/fl</sup>) and Fcgr2b heterozygous (Fcgr2b<sup>+/−</sup>) mice had comparable primary and secondary IgG responses, whereas these responses in Fcgr2b<sup>−/−</sup> mice were significantly enhanced (p < 0.001), consistent with previous studies (8, 33). Analyses of Fcgr2b conditional knockout lines showed that only mice with Mb1Cre have an increase of primary IgG Ab response equivalent to that of Fcgr2b<sup>−/−</sup> mice. Significant increase of secondary IgG responses were observed in both the Mb1Cre and Cg1Cre lines, whereas CD11cCre- and LysMCre-mediated deletion of Fcgr2b had no significant effect on either primary or secondary IgG responses. These results suggested that the effect of FcyRIIB deficiency on IgG Ab responses is B cell intrinsic, and FcyRIIB functions as a negative regulator in both primary and secondary IgG responses. Although FcyRIIB expressed in resting B cells is important to limit the primary Ab response, FcyRIIB expressed in B lineage cells at the GC or post-GC stages is important to inhibit the secondary response.

*FcyRIIB expression in DCs regulates T cell responses*

FcyRIIB expression in DCs has been reported to regulate T cell response, and we confirmed these reports (30). As shown in Fig. 3, in response to OVA immune complexes, significantly enhanced CD8 T cell response was observed in mice with either germline knockout or DC-specific knockout of Fcgr2b, suggesting that FcyRIIB expression in DCs could contribute to the maintenance of tolerance through regulating T cell responses.

**Increased spontaneous ANAs in mice with GC/post-GC B cell-specific deletion of FcyRIIB**

Because different autoimmune phenotypes have been reported in Fcgr2b knockout mice of different genetic backgrounds in previous studies (5, 8), we analyzed the Fcgr2b-knockout mice generated from B6 ES cells in this study. FcyRIIB deficiency resulted in modest but significant increases in IgG ANA titers in 10-mo-old B6 mice (p < 0.01), with ~25% displaying relatively high titers of ANAs (Fig. 4A). IgG ANAs were detectable in some Fcgr2b<sup>−/−</sup> mice by immunofluorescence staining of Hep-2 human ECs (Fig. 4B). When Fcgr2b conditional-knockout mice were analyzed for ANA IgG Abs, we found that conditional knockout of Fcgr2b by Cg1Cre in GC/post-GC B cells recapitulated the Fcgr2b germline-knockout phenotype, in contrast to CD11cCre- or LysMCre-mediated conditional knockouts (Fig. 4A), suggesting the FcyRIIB expression in GC or post-GC B cells is responsible for inhibiting the development of spontaneous autoantibodies.

**Increased arthritis incidence in mice with B cell– or DC-specific deletion of Fcgr2b on a nonpermissive background**

Previous studies have shown that Fcgr2b knockout mice are more susceptible to induced autoimmune diseases (6–8). To study the impact of germline or conditional knockout of Fcgr2b on the maintenance of tolerance, mice were analyzed in a bovine type II CIA (bCIA) model, which is normally nonpermissive in B6 mice because their H-2<sup>b</sup> background does not support sustained T cell and subsequent Ab responses against bovine type II collagen required to initiate and perpetuate bCIA (34–36). We found that FcyRIIB deficiency can sensitize B6 mice in this otherwise resistant model. As shown in Fig. 5, Fcgr2b<sup>−/−</sup> B6 mice are highly susceptible to bCIA (13 of 19; p < 0.0001), in contrast to the resistant WT B6 mice (0 of 23). The contribution of cell-specific FcyRIIB expression to the maintenance of tolerance was evaluated in this model using Fcgr2b conditional-knockout mice. As shown in Fig. 5, 9 of 20 Fcgr2b<sup>fl/fl</sup> mice with Mb1Cre-mediated selective deletion of Fcgr2b in B cells developed arthritis (p < 0.001), as did 3 of 10 Fcgr2b<sup>−/−</sup> mice with CD11cCre (p < 0.01). As heterozygous Fcgr2b mice (Fcgr2b<sup>+/−</sup>) generally did not develop arthritis, although a trend toward disease is suggested (2 of 17 mice, not statistically significant different from WT mice; Supplemental Fig. 2), heterozygous conditional-knockout mice with Mb1Cre or CD11cCre were also analyzed, and similar results were obtained (Supplemental Fig. 2). In contrast, Fcgr2b<sup>fl/fl</sup> mice...
FIGURE 5. Susceptibilities of mice with germline or conditional knockout of Fcgr2b to bCIA. Accumulative bCIA incidences in WT (Fcgr2bfl/fl) and the indicated mutant male mice with germline or conditional knockout of Fcgr2b are presented. n values are the numbers of mice in each group. Data are combined from three independent experiments with similar results. **p < 0.01, ****p < 0.0001, χ² test (versus the Fcgr2bfl/fl mice).

FIGURE 4. Spontaneous ANAs in WT and mutant mice with germline or conditional knockout of Fcgr2b. (A) Levels of ANAs of IgG classes in 10-mo-old WT and mutant mice with germline or conditional knockout of Fcgr2b (16–27 mice/group) were analyzed by ELISA and presented as O.D. values (symbols represent O.D. values of individual mice, and thick horizontal lines represent the means). (B) Increased ANA levels in some Fcgr2b−/− mice. Hep-2 human ECs were stained with 1:100 diluted sera from 8– to 9-mo-old WT and Fcgr2b−/− mice, followed by FITC-conjugated goat anti-mouse IgG. IgG ANAs were detected in about half (9 of 18) of Fcgr2b−/− mice, whereas none of 5 WT mice were positive in this analysis (p < 0.05, χ² test). Original magnification ×100. **p < 0.01, ANOVA with Dunnett post hoc comparing each group to the WT group.

with LysMCre did not develop statistically significant disease, excluding the contribution of CD11cCre activity in monocytes to the phenotype observed in Fcgr2bfl/fl mice with CD11cCre (Figs. 1A, 5). The significantly increased bCIA incidence in Fcgr2b conditional-knockout mice with either Mb1Cre or CD11cCre demonstrated that multiple cell compartments, including B cells and DCs, are involved in the development of CIA, and the regulation of these cells by FcyRIIB is critical to the maintenance of tolerance.

Increased arthritis severity in mice with GC/post-GC B cell–specific deletion of Fcgr2b on a permissive background

We also studied the impact of germline and conditional knockout of Fcgr2b on the maintenance of tolerance in the chicken type II CIA (cCIA) model. In contrast to the bCIA model, cCIA is permissive in B6 mice because a robust and sustained T cell response can be mounted against chicken type II collagen (34–36). As shown in Fig. 6A and 6B, whereas WT mice developed only mild arthritis, Fcgr2b−/− mice developed significantly more severe arthritis, consistent with previous reports (10). Analysis of conditional-knockout lines in this model showed that selective deletion of Fcgr2b in GC/post-GC B cells is sufficient to recapitulate the exacerbated arthritis phenotype in Fcgr2b−/− mice (Fig. 6A, 6B), which is in sharp contrast to the resistance of Fcgr2bfl/fl mice with Cg1Cre to bCIA (Fig. 5). Therefore, FcyRIIB expression in GC and/or post-GC B cells plays an important role in inhibiting autoimmunity in permissive models, but not in nonpermissive models.

Exacerbated arthritis in mice with selective deletion of Fcgr2b in myeloid effector cells in response to adoptively transferred arthritic sera

In previous studies, FcyRIIB has been shown to play an important role in modulating Ab-mediated effector functions by setting thresholds for immune complex activation of myeloid effector cells, which has been hypothesized to contribute to the maintenance of tolerance (8). We tested this hypothesis in a passive autoimmune model in which K/BxN autoreactive sera are adoptively transferred into mice with germline deletion of Fcgr2b or conditional deletion of Fcgr2b in myeloid effector cells by LysMCre. As shown in Fig. 7, administration of K/BxN sera leads to the development of arthritis in WT, but not FcyR-deficient (Fcer1g−/− Fcgr2b−/−) mice, whereas in Fcgr2b−/− mice, the development of arthritis was accelerated and exacerbated, consistent with the notion that although activating FcyRs is required for the development of K/BxN serum-induced arthritis, FcyRIIB negatively regulates Ab-triggered inflammation. LysMCre-mediated deletion of Fcgr2b, although not complete (Fig. 1A, 1C), resulted in near-total recapitulation of the effect of Fcgr2b germline deletion (Fig. 7), suggesting that the myeloid effector cells responsible for joint inflammation are very sensitive to Fcgr2b levels in this passive autoantibody transfer model of inflammation.
FIGURE 6. Susceptibilities of mice with germline or conditional knockout of Fcgr2b to the cCIA. (A) The development of cCIA in WT (Fcgr2b<sup>+/+</sup>) and the indicated mutant mice with germline or conditional knockout of Fcgr2b (11 to 12 mice/group), expressed as average arthritis clinical scores (mean ± SEM), is presented. (B) The distribution of the maximum arthritis clinical scores observed in the mice in (A) is presented. The p values were calculated by χ² test.

Discussion

The development of autoimmunity has been studied in several FcγRIIB-deficient mouse models, initially in Fcγr2b<sup>−/−</sup> mice derived from 129/Sv ES cells and backcrossed to either the B6 (B6.Fcgr2b<sup>129</sup>/<sup>−/−</sup>) or BALB/c background (5), and more recently in Fcγr2b<sup>−/−</sup> mice derived from B6 ES cells (8). The Fcγr2b<sup>−/−</sup> mice we independently generated from B6 ES cells (Fcγr2b<sup>129</sup>/<sup>−/−</sup>) showed significantly attenuated lupus-like phenotypes (proteinuria and premature mortality) as compared with the backcrossed B6. Fcγr2b<sup>129</sup>/<sup>−/−</sup> (N12) mice (Supplemental Table I), consistent with the report of Bolland and Revetch et al. (5). This is also consistent with the finding that in addition to FcγRIIB deficiency, the 129/Sv-derived Sle16 locus may be involved in the autoimmune phenotype in B6.Fcγr2b<sup>129</sup>/<sup>−/−</sup> mice based on the analysis of B6. Fcγr2b<sup>129</sup>/<sup>−/−</sup> mice with different lengths of 129/Sv DNA segments around the targeted Fcγr2b gene in a spontaneous arthritis model and an induced tolerance model (37, 38). Although these studies supported the conclusion from the early studies that Fcγr2b is an epistatic modifier of autoimmunity, it also demonstrated additional susceptibility factors contributed by 129/Sv genes that may have contributed to the severe proteinuria and premature mortality phenotypes observed in B6.Fcγr2b<sup>129</sup>/<sup>−/−</sup> mice (5). At the same time, we also observed several autoimmune phenotypes in Fcγr2b<sup>129</sup>/<sup>−/−</sup> mice, including the increased spontaneous ANA levels and susceptibility to bCIA or cCIA. These results, together with the previously reported moderate glomerulonephritis phenotype and increased incidence of anti–glomerular basement membrane diseases in Fcγr2b<sup>−/−</sup> mice derived from B6 ES cells (8, 39), confirmed that in B6 mice, FcγRIIB plays an important role in the maintenance of tolerance.

FcγRIIB is the most widely expressed of all FcγRs and found on essentially all lymphoid and myeloid subsets, with the exception of T and NK cells. This wide expression pattern has made the assignment of specific phenotypes of Fcγr2b-deficient mice to defined cellular populations difficult. The collection of Fcγr2b conditional-knockout strains generated in this study has provided us an opportunity to dissect the contribution of cell-specific FcγRIIB expression to a long list of FcγRIIB functions proposed based on the studies using Fcγr2b germline-knockout mice. In this study, we focused on the function of cell-specific FcγRIIB and its impact on the maintenance of tolerance. It has been hypothesized in a recent study that the contribution of FcγRIIB deficiency to autoimmunity is mainly through the regulation of Ab effector pathways, such as immune complex–mediated inflammation (5). This seems to be true in models that involve adoptive transfer of autoimmune Abs, such as the serum transfer K/BxN arthritis model in this study or the NTN model used in a previous study (40), as immune complex–mediated inflammation was enhanced in mice with selective deletion of Fcγr2b in myeloid effector cells by LysMCre or CEBPαCre. However, our analysis of Fcγr2b<sup>−/−</sup> mice with LysMCre in CIA models, in which autoreactive Abs are actively induced, does not support this hypothesis, as these mice are not more susceptible than WT mice to either bCIA or cCIA (data not shown). In contrast, we demonstrated that FcγRIIB expression in both B cells and DCs is important for the maintenance of tolerance in the bCIA model and that the contribution of B cell and dendritic FcγRIIB expression to the maintenance of tolerance might be based on different mechanisms.

We found that the effect of FcγRIIB deficiency on IgG Ab responses is B cell intrinsic, and FcγRIIB functions as a negative regulator in both primary and secondary IgG responses, suggesting that the activation of both resting B cells and memory B cells, in the primary and secondary responses, respectively, are both regulated by FcγRIIB. The deletion of Fcγr2b by B cell–specific Mb1Cre leads to significantly enhanced primary and secondary Ab responses, and the deletion of Fcγr2b by GC and post-GC B cell–specific Cg1Cre specifically enhanced the secondary Ab response, consistent with the timing when these Cres become active. FcγRIIB deficiency may contribute to increased Ab response by promoting B cell activation during the early stage and plasma cell survival during the late stage of B cell differentiation (3, 4, 33). The increased Ab responses in Fcγr2b<sup>−/−</sup> mice with Mb1Cre or Cg1Cre could contribute to the increased autoimmune phenotypes. These studies are consistent with the previous study showing that overexpression of a B cell–specific Fcγr2b transgene suppressed T-dependent IgG responses, spontaneous lupus, and chicken CIA phenotypes (41) and a more recent study showing that FcγRIIB expression from the autoimmunity-associated polymorphic allele was specifically reduced in GC B cells and resulted in...
a number of autoimmune phenotypes, including the development of more severe chicken CIA (10).

Interestingly, selective deletion of FcγRIIb by Mb1Cre and Cg1Cre, respectively, resulted in different autoimmune phenotypes. Although hypersensitive to CIA, FcγRIIb+ mice with Cg1Cre are not susceptible to bCIA, in contrast to FcγRIIb+ mice with Mb1Cre. Although this could be due to the different impact of Mb1Cre- and Cg1Cre-mediated FcγRIIb deletion on immune responses, it might be also related to the difference in these two different arthritis models. Although both CIA models require robust T cell and Ab responses to initiate and perpetuate arthritis, the H-2b background of B6 mice only support such responses against chicken, not bovine type II collagen (34–36). The fact that conditional knockout of FcγRIIb in APCs (DCs and B cells) resulted in the break of tolerance in the bCIA model suggests that these conditional knockouts of FcγRIIb might result in enhanced Ag presentation, which may lead to the observed increase in T cell and primary Ab responses in these mice and autoimmunity. In contrast, Cg1Cre-mediated deletion of FcγRIIb after B cell activation only results in increased secondary Ab response that is sufficient to enhance autoimmune response in the permissive cCIA model in which T cell tolerance is already broken. This notion is supported by increased anti-mouse type II collagen IgG levels in FcγRIIb−/− mice with Cg1Cre (Supplemental Fig. 5).

We also confirmed previous studies showing that FcγRIIB expression in DCs can inhibit T cell response (42), presumably by regulating DC maturation and Ag presentation. This is consistent with other studies showing that selective blockade of FcγRIIB can promote DC maturation and T cell responses (43–45). Previous studies using B6.FcγR2b129−/− mice in the experimental autoimmune encephalomyelitis model suggested the impact of FcγRIIB expression on T cell responses could contribute to the maintenance of tolerance (46). Our study, together with that of van Montfoort et al. (30), established that the increased T cell response in FcγRIIB-deficient B6 mice may contribute to autoimmunity. In addition, FcγRIIB has been previously shown to set thresholds for immune complex–triggered inflammation in a number of animal models presumably by regulating myeloid effector cells. In this study, partial deletion of FcγRIIB on myeloid effector cells leads to significantly exacerbated arthritis triggered by K/BxN sera, suggesting that myeloid effector cells are very sensitive to the regulation by FcγRIIB levels, in agreement with our finding that increased FcγRIIB expression in myeloid effector cells in response to IVIG is responsible for its significant anti-inflammatory effects in vivo (29, 47, 48).

Our data also showed that quantitative changes in immune responses due to selective deletion of FcγR2b can result in significant differences in autoimmune models. In corroboration with this notion, previous studies have shown a quantitative increase in TLR7 expression due to gene duplication can accelerate the development of autoimmune diseases (49, 50). These findings suggest that the maintenance of tolerance involves many checkpoints that do not qualitatively but quantitatively regulate immune system at various levels, highlighting the importance of the balance in immunoregulatory networks.

Taken together, through the analysis of a collection of novel FcγRIIB conditional-knockout strains with specific deletion of FcγR2b in defined cellular compartments, we demonstrated that FcγRIIB expression in multiple cellular compartments is required for the maintenance of peripheral tolerance through different mechanisms, and FcγRIIB expression in the same cell lineage (B cells) but at different differentiation stages also has a different impact on the maintenance of tolerance. This collection of FcγRIIB conditional-knockout strains is likely useful to investigate other functions assigned to FcγRIIB. For instance, FcγRIIB coengagement has been recently found to be necessary for the in vivo activities of agonistic Abs to the TNFR family members, such as CD40 and DR5 (51, 52), and these conditional FcγR2b knockout mice might be also useful to dissect the contribution of cell-specific FcγRIIB to the activities of these Abs.

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Disclosures

The authors have no financial conflicts of interest.

References

Supplementary Figure 1 Generation of \( Fcgr2b^f \) and \( Fcgr2b^b \) mice. (A) Strategy used to generate mice with loxP-flanked \( Fcgr2b \) alleles (\( Fcgr2b^f \)). Shown are schematic maps of the wild-type \( Fcgr2b \) allele, targeting vector, targeted alleles before (\( Fcgr2b^{fl/neo} \)) and after (\( Fcgr2b^b \)) the loxP-flanked neomycin-resistant gene (neo) cassette is deleted by Cre, as well as the \( Fcgr2b^b \) allele. The exons of the \( Fcgr2b \) gene (S1, S2, EC1, EC2, TM, IC1, IC2, IC3) are shown as vertical bars; grey triangles represent loxP sites; wide empty arrow labeled with “NEO” is the neomycin-resistant gene; vertical lines labeled as “RV” represent EcoR V restriction sites and the relevant EcoR V fragments are shown using dashed line labeled with the sizes; spiky circles represent probe for Southern blot; the sites of two forward PCR primers (pR2floxA and pNeo-cF1) and two reverse primers (pNeo-R1 and pR2delta4.2) are shown as bended arrows. The targeting vector is designed to generate a targeted \( Fcgr2b \) allele (\( Fcgr2b^{fl/neo} \)) with a loxP site inserted between the S1 and EC1 exons, and a loxP flanked neo cassette between the TM and IC1 exons after the desired recombination between the targeting vector and the WT \( Fcgr2b \) allele in ES cells. The loxP-flanked neo cassette can be deleted by Cre in ES cells to generate the \( Fcgr2b^f \) allele that has two loxP sites flanking the region between the S2 and TM exons. The region between the two distal loxP sites can be deleted by Cre to generate the \( Fcgr2b^b \) allele. (B) Identification of ES clones containing the \( Fcgr2b^{fl/neo} \) targeted allele (after the endogenous WT \( Fcgr2b \) gene recombines with the targeting vector) by Southern blot using EcoR V digested ES cell genomic DNA the probe shown in (A). One of the positive clones, #231 was picked for the downstream experiments. (C) Identification of ES clones with the \( Fcgr2b^f \) allele (after ES clone #231 was transiently transfected with a Cre-expression construct) by PCR using primers pR2floxA and pRdelta4.2, which generate a 0.5 kb product specific from the \( Fcgr2b^f \) allele, and a 2.5kb product from the \( Fcgr2b^{lineo} \) allele, and no product from other alleles. (D) Confirmation of the deletion of the neo cassette by PCR using the indicated primers. Among several clones that are positive for the \( Fcgr2b^f \) allele and the deletion of neo cassette, #39 was picked for further development of mice carrying the \( Fcgr2b^f \) allele.
Supplementary Figure 2 Susceptibilities of mice with germline or conditional knockout of Fcgr2b to bovine type II collagen induced arthritis (bCIA). Accumulative bCIA incidences in WT (Fcgr2b\textsuperscript{fl/fl}) and the indicated mutant male mice with germline or conditional knockout of Fcgr2b on the heterozygous Fcgr2b\textsuperscript{fl} background are presented. “n” values are the numbers of mice in each group. *** \( p < 0.001 \), **** \( p < 0.0001 \), Chi-square test (vs the “Fcgr2b\textsuperscript{fl/fl}” mice).
Supplementary Figure 3. Mouse type II collagen-specific IgG responses in mice with germline or conditional knockout of Fcgr2b in the chicken type II collagen induced arthritis (cCIA) model. Fcgr2b<sup>fl/fl</sup>, Fcgr2b<sup>−/−</sup>, and Fcgr2b<sup>fl/fl</sup>Cg1Cre<sup>+</sup> mice were treated with chicken type II collagen in adjuvant to induce arthritis. Levels of mouse type II collagen-specific IgG were analyzed two months later by ELISA and presented as O.D. values (mean±s.d. and individual values plotted). *** p < 0.001, ANOVA with Tukey’s post hoc (additional statistical test results: “Fcgr2b<sup>−/−</sup>” vs “Fcgr2b<sup>fl/fl</sup>”, p < 0.05 in t-test; “Fcgr2b<sup>fl/fl</sup>, Cg1Cre<sup>+</sup>” vs “Fcgr2b<sup>fl/fl</sup>”, p < 0.01 in F-test).
Supplementary table: premature mortality and proteinuria phenotypes in FcyRIIB-deficient mice

<table>
<thead>
<tr>
<th>Strain</th>
<th>Age (month)</th>
<th>Total number of mice</th>
<th>Mortality</th>
<th>Sick&lt;sup&gt;a&lt;/sup&gt;</th>
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<td>5</td>
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<tr>
<td><em>B6.Fcgr2b&lt;sub&gt;129&lt;/sub&gt;</em>/&lt;sup&gt;+&lt;/sup&gt; (N12)</td>
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<td>29</td>
<td>18</td>
<td>9</td>
<td>93</td>
</tr>
</tbody>
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<sup>a</sup>“sick” is define as proteinuria levels 100 mg/dL or above.