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Cd72c Is a Modifier Gene that Regulates Faslpr-Induced Autoimmune Disease

Miduo Xu,∗† Rong Hou,∗† Aya Sato-Hayashizaki,∗† Rongyong Man,∗† Chenghua Zhu,∗† Chisato Wakabayashi,∗† Sachiko Hirose,† Takahiro Adachi,∗† and Takeshi Tsubata∗†

Although modifier genes are extensively studied in various diseases, little is known about modifier genes that regulate autoimmune diseases. Autoimmune disease caused by the Faslpr mutation depends on the genetic background of mouse strains, suggesting a crucial role of modifier genes. MRL/MpJ-Faslpr (MRL/lpr) and AKR/lpr mice develop severe and mild lupus-like autoimmune disease, respectively, whereas this mutation does not cause disease on C57BL/6 (B6) or C3H background. Both MRL and AKR carry the same haplotype of the Cd72 gene encoding an inhibitory BCR coreceptor (CD72c), and CD72c contains several amino acid substitutions and a deletion in the extracellular region compared with CD72a and CD72b. To address the role of Cd72c locus in the regulation of Faslpr-induced autoimmune disease, we generated B6.CD72c/lpr and MRL.CD72b/lpr congenic mice. Introduction of the chromosomal interval containing Cd72c did not cause disease in B6 mice by itself, but caused development of lupus-like disease in the presence of Faslpr on B6 background, clearly demonstrating that this interval contains the modifier gene that regulates Faslpr-induced autoimmune disease. Conversely, MRL.CD72b/lpr congenic mice showed milder disease compared with MRL/lpr mice. We further demonstrated that Cd72c is a hypofunctional allele in BCR signal inhibition and that CD72 deficiency induces severe autoimmune disease in the presence of Faslpr. These results strongly suggest that the Cd72c is a crucial modifier gene that regulates Faslpr-induced autoimmune disease due to its reduced activity of B cell signal regulation.

M

odifier genes have been extensively studied in various diseases such as cancer, arrhythmia, and cystic fibrosis, because penetrance and disease manifestations of the disease caused by disease-causing genes are extensively modified by modifier genes (1–3). In cystic fibrosis, contribution of modifier genes to the disease variability is almost equivalent to that of environmental factors. Mutation of the Fas gene causes autoimmune disease in both mice and human (4–7). Penetration, severity, and manifestations of the disease induced by Faslpr mutation, a loss-of-function mutation of Fas, depend on the genetic background of mouse strains. MRL/MpJ-Faslpr (MRL/lpr) and AKR/lpr mice develop severe and mild lupus-like autoimmune disease, whereas Faslpr does not induce autoimmune disease in C57BL/6 and C3H mice (8, 9). Moreover, Fas-deficient BALB/c mice were recently shown to develop allergic inflammation (10). Thus, the disease caused by Faslpr or Fas deficiency is strongly regulated by modifier genes.

CD72 is a 45-kDa type II membrane protein expressed in B cells. CD72 contains a C-type lectin-like domain in the extracellular region and an immunoreceptor tyrosine-based inhibition motif (ITIM) in the cytoplasmic region (11–13). CD72 negatively regulates BCR signaling by recruiting SH2-containing tyrosine phosphatase-1 at the ITIM (12–16). In mice, four allelic forms of CD72 (i.e., CD72a, CD72b, CD72c, and CD72d) were serologically defined (17). CD72a, CD72b, and CD72d are highly homologous (18, 19). In contrast, the extracellular region of CD72c has a marked difference from the other alleles including a 7 aa deletion in the C-type lectin-like domain, although the amino acid sequence of the transmembrane and cytoplasmic regions of CD72c is identical to that of the other alleles (18, 19). Interestingly, MRL and AKR, both of which develop autoimmune disease in the presence of Faslpr, carry CD72c, whereas most of the other strains of mice, including BALB/c and C57BL/6 (B6), carry either CD72a or CD72b (18, 19). Moreover, studies using microsatellite markers revealed association of the loci containing Cd72 to development of glomerulonephritis in MRL/lpr mice (20–22). Thus, Cd72c is a candidate for a modifier gene that regulates Faslpr-induced autoimmune disease.

In this study, we addressed the role of the Cd72c locus in the development of autoimmune disease by generating B6.CD72c and MRL.CD72b/lpr congenic mice. B cells from B6.CD72c congenic mice showed augmented BCR signaling compared with B6 B cells, and B6.CD72c/lpr developed severe autoimmune disease, whereas B6.CD72c mice showed no disease. Conversely, MRL.CD72b/lpr mice showed less severe autoimmune disease compared with MRL/lpr mice. These results suggest that Cd72c is a functionally defective allele, and the Cd72c locus does not cause any disease by itself but plays a role in development of severe autoimmune disease in MRL/lpr mice probably by augmenting BCR signaling. We further demonstrate that CD72 deficiency causes severe autoimmune disease in the presence of Faslpr by generating CD72-deficient mice. Thus, Cd72c is a modifier gene that plays a crucial role in development of Faslpr-induced autoimmune disease probably through its defective regulatory function on BCR signaling.
Materials and Methods

Cell lines

The mouse B cell line BAL17 and its transfectants were cultured in RPMI 1640 medium supplemented with 10% FCS, 50 μM 2-ME, 1 mM d-glutamine, and 100 U penicillin/streptomycin. The retrovirus packaging cell line PLAT-E (a gift of Dr. T. Kitamura, University of Tokyo, Tokyo, Japan) (23) was maintained in DMEM supplemented with 10% FCS, 2 mM l-glutamine, and 100 U penicillin/streptomycin. Embryonic stem (ES) cells line R-CMTT-2A derived from B6 mice was purchased from Dainippon Sumitomo Pharma (Osaka, Japan) and was cultured in DMEM medium supplemented with 15% FBS, l-glutamine, nonessential amino acids, and LIF (Chemicon International).

Vector and retrovirus

The CD72<sup>+</sup> and CD72<sup>-</sup> cDNA was obtained from total RNA prepared from a DBA/2 and MRL/lpr mouse spleen, respectively, by RT-PCR using a set of primers (5′-CCGATATCGGCTGACCTATACG-3′ and 5′-AAGCGGCGCTATATCCGGTTCAGTTCAG-3′). These fragments were inserted into the retroviral vector pMX (a gift of Dr. T. Kitamura) (24). For retrovirus production, the packaging cells were transfected with retroviral vectors using a calcium phosphate method. Cells were cultured for 48 h, and the culture supernatant was collected. BAL17 cells were incubated with the supernatant containing retrovirus in the presence of 5 μg/ml polybrene for 4 h.

Mice

B6 and MRL/lpr mice were purchased from Sankyo Laboratory Service (Tokyo, Japan). B6/lpr mice were purchased from Japan SLC (Hamamatsu, Japan). QM mice were as described previously (25) (a kind gift from Dr. M. Wabl, University of California, San Francisco, CA). To generate CD72-deficient mice, genomic DNA fragments containing Cd72 were isolated by PCR from the bacterial artificial chromosome (BAC) DNA derived from a B6 mouse. The targeting vector was constructed by inserting the neomycin resistance gene flanked by the lox<sup>P</sup> sequence amplified from the first exon of Cd72 (Supplemental Fig. 2A). The linearized targeting vector was transfected by electroporation into the R-CMTT-2A ES cells. The Cd72<sup>+</sup> ES cells 4 and 150 (Supplemental Fig. 2B) were used for blastocyst injection to generate chimeric mice. Lack of Cd72 expression in Cd72<sup>-</sup> mice was confirmed by flow cytometry and Western blotting (Supplemental Fig. 2C, 2D). All mice used in this study were bred and maintained in a specific pathogen-free animal facility of Tokyo Medical and Dental University and handled according to our institutional guidelines.

Genotyping

Genomic DNA was extracted from mouse tail and genotyping was done by PCR. Microsatellite primers D4M1628, D4M1913, D4M1916, D4M911, D4M1241, D4M919, D4M308, and D4M203, located at 8.73, 13.99, 20.16, 23.04, 30.48, 33.96, 43.34, and 57.66 cM distal from the centromere on chromosome 4, respectively, were synthesized according to Mouse Genome Informatics (The Jackson Laboratory). The Cd72<sup>+</sup> and Cd72<sup>-</sup> allele were specifically amplified using the following primers sets: Cd72<sup>-</sup> forward, 5′-CATATACACAGAAGGGA-3′ and reverse, 5′-GGTTAAGGATGTAGGTCACAAGGTCTT-3′; and Cd72<sup>+</sup> forward, 5′-ATATATAACAAGAAGTGGGC-3′ and reverse, 5′-GGTTAAGGATGTAGGTCACAAGGTCTT-3′. 

Flow cytometry analysis

Single-cell suspensions were prepared and stained with the following Abs: FITC-conjugated anti-CD3ε mAb (53-7.3), FITC-conjugated anti-CD21 mAb (7E9) (BioLegend); PE-conjugated anti-CD23 mAb (B3B4), PE-conjugated anti-CD72<sup>+</sup>-mAb (JY/93; BD Pharmingen); FITC-conjugated anti-CD72<sup>-</sup>-mAb (Y9J3; BD Pharmingen); PE-conjugated anti-human IgM Ab (Southern Biotechnologies Associates). FACS analysis was performed using a FACSCalibur (BD Biosciences) or a CyAn ADP (DakoCytomation) and analyzed using the FlowJo software (Tree Star) or Summit software (DakoCytomation), respectively.

ELISAs

Serum levels of total IgG were measured by standard sandwich ELISA. Titers of IgG Ab to dsDNA, ssDNA, and chromatin were measured by ELISAs as described previously (27). Briefly, ELISA plates were coated with 10 μg/ml dsDNA, 10 μg/ml ssDNA, or 4 μg/ml chromatin. After blocking with 0.5% BSA in PBS, 50 μl diluted serum samples were added and incubated for 60 min at room temperature. Plates were then washed and incubated with alkaline phosphatase–conjugated goat anti-mouse IgG Ab (Southern Biotechnologies Associates). After washing, plates were reacted by phosphatase substrate (Sigma-Aldrich), and the absorbance at 405 nm was measured on a Vmax kinetic microplate reader ( Molecular Devices). Autoantibody titers were determined using the sera pooled from (NZB × NZW) F1 mice >8 mo old as a standard.

Immunoprecipitation and Western blotting

B cells were purified from mouse spleen as described previously (28) and were stimulated with 0.2 μg/ml 4-hydroxy-3-nitrophenyl acetyl (NP)-BSA or 10 μg/ml F(ab′<sub>2</sub>) fragments of goat anti-mouse IgM Ab (Jackson ImmunoResearch Laboratories). Alternatively, BAL17 cells were stimulated with 10 μg/ml F(ab′<sub>2</sub>) fragments of goat anti-mouse IgM Ab at 37°C. Cells were lysed in Triton X-100 lysis buffer (1% Triton X-100, 100 mM glycerc, 150 mM sodium chloride, 20 mM Tris-HCl, 2 mM EDTA, 0.02% sodium azide, 10 μg/ml PMSF, and 1 mM sodium orthovanadate) and immunoprecipitated with rat anti-Cd72 mAb JY/93 (BD Pharmingen) using protein G-Sepharose (Amersham Biosciences). Total cell lysates or immunoprecipitates were separated by SDS-PAGE and transferred to polyvinylidene difluoride membranes (Millipore). Membranes were incubated with goat anti-mouse IgG/F(ab′<sub>2</sub>) mAb (Southern Biotechnologies Associates), rabbit anti-Cd72 Ab (Santa Cruz Biotechnology), or rabbit anti-p42/44 ERK Ab (Cell Signaling Technology), followed by reaction with HRP-conjugated donkey anti-goat IgG Ab (Santa Cruz Biotechnology) or HRP-conjugated goat anti-rabbit IgG Ab (Southern Biotechnologies Associates). Alternately membranes were incubated with mouse anti-β-tubulin Ab (TUB2.1) (Seikagaku Kogyo), followed by reaction with HRP-conjugated goat anti-mouse IgG Ab (Southern Biotechnologies Associates). Proteins were then visualized using ECL system (Amersham Biosciences). The intensity of protein bands was quantified using the Image J software (National Institutes of Health).

Measurement of intracellular calcium concentration

Spleen B cells were purified as described previously (29). BAL17 cells and its transfectants or purified spleen B cells (1 × 10<sup>5</sup>) were incubated in culture medium containing 5 μg Fluo-4/AM (Molecular Probes) at 37°C for 30 min. Cells were stimulated with 10 μg/ml F(ab′<sub>2</sub>) fragments of anti-IgM Ab or 0.2 μg/ml NP-BSA, and fluorescence was continuously measured by an FACSCalibur (BD Biosciences) for a total of 300 s.

Measurement of cell proliferation by CFSE dilution

Spleen B cells were purified as described previously (28) and labeled with 5 μM CFSE (Molecular Probes). The purity of purified cells was determined by flow cytometry using anti-B220 Ab staining (purity >95%). Cells (2 × 10<sup>5</sup>) were then seeded into 96-well plate and cultured in RPMI 1640 medium supplemented with 10% FCS, 50 μM 2-ME, 1 mM d-glutamine, and 100 U penicillin/streptomycin with or without 10 μg/ml anti-CD40 Ab (FGK45) (30), 10 μg/ml F(ab′<sub>2</sub>) fragments of goat anti-mouse IgM Ab (Jackson ImmunoResearch Laboratories), or 10 ng/ml CpG oligomer (ODN 1668) (31) at 37°C for 72 h. The fluorescence of CFSE was measured by a CyAn ADP (DakoCytomation).

Histopathological and immunohistochemical analysis

Mice were sacrificed, and tissues were fixed in neutral buffered formalin and embedded in paraffin according to standard practices. Tissue sections (5 μm) were stained with either H&E or periodic acid-Schiff and hematoxylin (PASH). Glomerular damages were scored as described previously (32). For immunohistochemical analysis, portions of kidney were embedded in Tissue-Tek OCT compound (Sakura) and snap frozen in liquid nitrogen. Cryostat sections (7-μm thickness) were mounted onto slide glass. The sections were incubated with blocking buffer (PBS containing 0.5% BSA and 0.05% sodium azide) for 30 min and stained with FITC-conjugated anti-mouse IgG Ab (Cappel) or FITC-conjugated anti-mouse IgA C3 (Cappel) at room temperature for 1 h. Sections were analyzed using a laser-scanning microscopy Leica DMi6000B (Leica Microsystems).

Detection of proteinuria

The protein level of mouse urine was semiquantitatively analyzed as described previously (33).

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Statistical analysis

The data are presented as the means ± SEM, and all statistical analyses were performed using GraphPad Prism 5.0 software (GraphPad). The p values were calculated with the two-tailed Student t test (*p < 0.05, **p < 0.01, ***p < 0.001).

Results

Spontaneous development of lupus-like disease in B6.CD72c/lpr congenic mice

B6/lpr and C3H/lpr mice are reported to show no or only a mild autoimmune disease (8, 9), whereas AKR/lpr and MRL/lpr mice develop moderate and severe lupus-like disease, respectively, suggesting that some genes carried by AKR and MRL mice are required for FasIpr-induced autoimmune disease. To address whether such a gene is located in the Cd72c locus carried by both AKR and MRL, we generated B6.CD72c congenic mice carrying the MRL-derived Cd72c haplotype by selective backcrossing of the F1 hybrid between B6 carrying Cd72b and MRL mice to B6 mice for 11 generations. Microsatellite marker analysis revealed that B6.CD72c mice carry an MRL/lpr-derived interval on chromosome 4 containing the Cd72c locus (Supplemental Fig. 1A). We then generated B6.CD72c/lpr mice by crossing B6.CD72c mice with B6/lpr mice. B6.CD72c/lpr mice at 12 mo of age showed marked splenomegaly (Fig. 1A) and moderate lymphadenopathy (data not shown) compared with B6/lpr mice, whereas the spleen weight in B6.CD72c mice was similar to that in B6 mice. Flow cytometry analysis revealed that percentages of T cells and B cells in both spleen and lymph nodes (LNs) of B6.CD72c mice were

FIGURE 1. Lupus-like disease in B6.CD72c/lpr congenic mice. (A–E) One-year-old female B6, B6.CD72c, B6/lpr, and B6.CD72c/lpr mice (n = 6–11) were analyzed. (A) Spleen weight. (B) Concentrations of total IgG and titers of indicated autoantibodies in sera. Horizontal bars represent mean values. For determining autoantibody titers, pooled sera from >8-mo-old (NZB × NZW)F1 mice are used as a standard (1000 U/ml). (C) PASH staining of glomeruli. Severity of glomerular damage was scored as described previously (32). Grade 0, no involvement; grades 1, 2, and 3, changes in 0–25%, 25–50%, and 50–75% of total glomeruli, respectively; grade 4, sclerosis or crescent formation in >90% of glomeruli. Scale bars, 50 μM. (D) Immunohistochemical analyses for IgG and C3 in glomeruli. Scale bars, 50 μM. (E) H&E staining of liver and lung. Representative data of more than five mice in each genotype are shown (original magnification ×100). Severity of the disease was scored according to the degree of lymphocyte infiltration. Grade 0, no lymphocyte infiltration; grade 1, moderate lymphocyte infiltration; and grade 2, severe lymphocyte infiltration. (F) Serum titer of anti-ssDNA IgG. Six-month-old female B6, B6.CD72c, B6/lpr, B6.CD72c/lpr, and MRL/lpr mice were analyzed (n = 3–10). *p < 0.05, **p < 0.005, ***p < 0.001.
similar to those of B6 mice (Table I). In contrast, B6.CD72c/lpr mice showed marked reduction in the percentage of B cells and increase in the percentage of T cells compared with B6/lpr mice. The percentage of B220+CD3+ lpr T cells in B6.CD72c/lpr mice was not increased compared with B6/lpr mice. Thus, introduction of the interval of chromosome 4 containing Cd72 locus induced marked splenomegaly and altered T cell to B cell ratio in B6/lpr but not B6 mice, suggesting that the chromosomal interval containing Cd72 locus does not modulate immune homeostasis by itself, but does so in the presence of Fas+ mutation.

Next we examined development of autoimmune disease in B6.CD72c/lpr mice. Sera from 12-mo-old B6.CD72c/lpr mice contained a much larger amount of IgG autoantibodies such as anti-dsDNA, anti-ssDNA, and anti-chromatin Abs compared with B6/lpr mice (Fig. 1B). Histopathological and immunohistological analysis of kidney revealed that B6.CD72c/lpr mice developed renal disease in MRL/lpr mice, especially in expansion of lpr T cells and autoantibody production. We analyzed 6-mo-old female MRL.CD72b/lpr mice and between MRL.CD72b/lpr and B6/lpr mice for 12 genera-

Augmented BCR signaling and B cell proliferation in B cells carrying Cd72c

To elucidate whether Cd72c is functionally distinct from Cd72b, we crossed B6.CD72c mice with the QM mice on a B6 background expressing Cd72b to generate QM.CD72c mice. As almost all B cells from QM mice express BCR reactive to hapten NP due to their expression of knocked-in VH17.2.25 and λ L chain (25), we ligated BCR in spleen B cells from QM mice and QM.CD72c mice using an Ag NP-conjugated BSA and examined BCR signaling by analyzing calcium mobilization and phosphorylation of ERK. Although the Ca2+ response in QM.CD72c B cells was similar to that in QM B cells (Fig. 3A), QM.CD72c B cells showed augmented ERK phosphorylation compared with QM B cells (Fig. 3B).

Next, we addressed proliferative response of Cd72c-carrying B cells to various stimuli by CFSE dilution assay. When purified spleen B cells from B6 and B6.CD72c mice were stimulated with CpG oligomers or anti-CD40 Ab, percentage of proliferated cells were significantly higher in B6.CD72c cells than in B6 B cells (Fig. 3C). However, percentage of divided cells after anti-IgM stimulation was not increased in B6.CD72c B cells compared with B6 B cells probably because B6 B cells fully proliferated to this stimulation. Thus, Ag-induced ERK activation and proliferative response to CpG and anti-CD40 Ab were augmented in B6.CD72c B cells, suggesting that Cd72c negatively regulates B cell activation less efficiently than Cd72b does, although the possibility that the other

Table I. Flow cytometry analysis of spleen and LN cells from B6, B6.CD72c, B6/lpr, and B6.CD72c/lpr mice

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Cell Population</th>
<th>B6</th>
<th>B6.CD72c</th>
<th>B6/lpr</th>
<th>B6.CD72c/lpr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total cell number (×10^6)</td>
<td>145.0 ± 11.0</td>
<td>127.0 ± 9.2</td>
<td>320.0 ± 100.0</td>
<td>764.3 ± 38.9*</td>
</tr>
<tr>
<td></td>
<td>Phenotype (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B220+CD3 (B cells)</td>
<td>55.9 ± 3.1</td>
<td>56.0 ± 6.9</td>
<td>46.4 ± 3.9</td>
<td>18.1 ± 5.8**</td>
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<tr>
<td></td>
<td>(×10^6)</td>
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<td>(69.2 ± 11.9)</td>
<td>(133.4 ± 38.3)</td>
<td>(137.6 ± 47.6)</td>
</tr>
<tr>
<td></td>
<td>CD3+B220 (T cells)</td>
<td>25.5 ± 3.2</td>
<td>20.3 ± 6.3</td>
<td>24.3 ± 3.4</td>
<td>40.5 ± 4.5*</td>
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<td></td>
<td>(×10^5)</td>
<td>(37.9 ± 6.4)</td>
<td>(24.3 ± 9.9)</td>
<td>(89.2 ± 35.4)</td>
<td>(315.8 ± 43.4)**</td>
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<td></td>
<td>CD20+CD3− (B cells)</td>
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<td></td>
<td>(×10^6)</td>
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<td>(27.6 ± 9.6)</td>
<td>(84.0 ± 30.9)</td>
<td>(255.4 ± 75.8)**</td>
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<td></td>
<td>B220+CD3− (lpr T cells)</td>
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<td>6.7 ± 2.3</td>
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<td>(×10^5)</td>
<td>(3.4 ± 1.3)</td>
<td>(1.6 ± 0.6)</td>
<td>(3.4 ± 3.7)</td>
<td>(55.5 ± 21.2)*</td>
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<tr>
<td>LN</td>
<td>Phenotype (%)</td>
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<tr>
<td></td>
<td>B220+CD3 (B cells)</td>
<td>52.9 ± 6.3</td>
<td>44.2 ± 6.9</td>
<td>43.3 ± 3.0</td>
<td>17.9 ± 7.5*</td>
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<td>(27.3 ± 3.0)</td>
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Data were obtained from 12–14-mo-old mice and are expressed as mean ± sem (n = 6 to 7).

*p < 0.05, **p < 0.01.
genes in the MRL-derived interval in B6.CD72⁻ mice regulate B cell activation is not excluded.

To directly demonstrate that CD72⁻ poorly regulates BCR signaling, we transduced CD72⁻ and CD72⁺, the latter of which is highly homologous to CD72⁻, to the mouse B cell line BAL17 and examined their capacity to regulate BCR signaling. As BAL17 cells express endogenous CD72⁺ (34), we examined the expression of the transduced CD72⁻ and CD72⁺ by flow cytometry using anti-CD72 mAbs reactive to CD72⁻ and CD72⁺ and that reactive to CD72⁻ and CD72⁺, respectively. The expression level of CD72 in BAL17-CD72⁻ transfectant and BAL17-CD72⁺ transfectant are 1.74 and 3.58 times higher than parent BAL17 cells, respectively (Fig. 3D). We are not able to exclude the possibility that these anti-CD72 Abs react to different CD72 allelic forms with different efficiency or the possibility that transduced CD72 affects expression of endogenous CD72 or forms a heterodimer with endogenous CD72. Nonetheless, our result on flow cytometry suggests that CD72⁻ expression in BAL17-CD72⁻ cells is higher than CD72⁺ expression in BAL17-CD72⁺ cells. We then ligated BCR on BAL17 transfectants using anti-IgM Ab and analyzed calcium mobilization and ERK phosphorylation. Both calcium mobilization and ERK phosphorylation induced by BCR ligation were reduced in BAL17-CD72⁻ transfectant compared with control transfectant (Fig. 3E, 3F), indicating that CD72⁻ negatively regulates BCR signaling in agreement with previous findings (14). In contrast, CD72⁺ expression reduced both calcium mobilization and ERK phosphorylation only marginally if any (Fig. 3E, 3F), although the CD72 expression level in CD72⁻ transfectant is higher than that in CD72⁺ transfectant. Thus, CD72⁻ regulates BCR signaling less efficiently than CD72⁺ in both primary B cells and BAL17 cells.

CD72⁻ differs from CD72⁺ or CD72⁺ at the extracellular part but not the cytoplasmic region including ITIM. To address how the extracellular part of CD72⁻ reduces its negative-regulatory activity on B cell activation, we examined association of CD72 to BCR. When we immunoprecipitated CD72⁻ and CD72⁺ from lysates of B6 and B6.CD72⁻ B cells, respectively, CD72⁻ coprecipitated more IgM than CD72⁺ did (Fig. 3G). This result suggests that CD72⁻ associates with BCR less strongly than CD72⁺ does, although we are not able to exclude the possibility that anti-CD72 Abs differently react to the different CD72 allelic forms, resulting in different immunoprecipitation and detection efficiency depending on the allelic forms. Taken together, CD72⁻ regulates B cell signaling and B cell activation inefficiently probably due to its weak association to BCR.

**CD72 deficiency causes severe autoimmune disease in the presence of Faslpr mutation**

As CD72⁻ regulates BCR signaling less efficiently than CD72⁺, we next addressed whether CD72 deficiency induces severe autoimmune disease in the presence of the Faslpr gene by generating CD72⁻⁻ mice on a B6 background (Supplemental Fig. 2). When we examined signaling properties of CD72⁻⁻ B6 B cells, BCR ligation–induced ERK phosphorylation was augmented compared with that in wild-type B6 B cells expressing CD72⁺ (Fig. 4A), whereas calcium signaling in CD72⁻⁻ B cells was similar to that

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**FIGURE 2.** Reduced severity of autoimmune disease in MRL.CD72⁻⁻ mice. Female MRL/lpr and MRL.CD72⁻⁻ mice at 6 mo old were analyzed. (A) Spleen weights (n = 10–16). (B) Percentages of lpr T cells (B220⁺CD3⁺), B cells (B220⁺CD3⁻), and T cells (B220⁻CD3⁻) in total lymphocyte-gated splenocytes were measured by flow cytometry (n = 3). (C) Concentrations of total IgG and titers of anti-dsDNA and anti-ssDNA IgG in sera were measured by ELISA (n = 5–9). For determining autoantibody titers, pooled sera from 2–3-mo-old (NZB × NZW) F1 mice are used as a standard (1000 U/ml). (D) Percentages of lpr T cells (B220⁺CD3⁺), B cells (B220⁺CD3⁻), and T cells (B220⁻CD3⁻) in total lymphocyte-gated splenocytes were measured by flow cytometry (n = 3). (E) Immunohistochemical analysis of glomeruli for IgG and C3. Representative data of more than three mice in each genotype are shown. Scale bars, 50 μM. (G) Severity of glomerular damage was scored as in the legend to Fig. 1C. Glomeruli are shown at the same magnification. Scale bars, 50 μM.

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Urine protein level. Urine was spotted on filter paper, and the protein level was semiquantitatively measured (n = 7–12). The grade of proteinuria was defined as follows: grade 6, equivalent to 30 mg/ml BSA; grade 5, 10 mg/ml BSA; grade 4, 3.3 mg/ml BSA; grade 3, 1.1 mg/ml BSA; grade 2, 0.74 mg/ml BSA; and grade 1, 0.37 mg/ml BSA. *p < 0.05, **p < 0.005.
anti–CD72c mice were immunoprecipitated (IP) with anti-CD72 or control Ab and analyzed by Western blotting using anti-IgM and anti-CD72 Abs. Calcium ion concentration was analyzed by flow cytometry. The percentages of proliferated cells are indicated (right panel). Data are representative of three independent experiments. (D) CD72 expression in indicated BAL17 transfectants were analyzed by flow cytometry using anti-CD72 Abs K10.6 reactive to CD72a and CD72b and JY/93 reactive to CD72b and CD72c. Mean fluorescence intensity (MFI) is indicated. Unstained cells were used as negative controls (shaded histograms). Fluo-4/AM–loaded (E) or untreated (F) BAL17 transfectants were stimulated with 10 μg/ml anti-IgM Ab. Calcium ion concentration was analyzed by flow cytometry (E). The arrowhead indicates the time point when anti-IgM Ab was added. Representative data of five experiments are shown. Total cell lysates were analyzed for phosphorylation of ERK by Western blotting (F). The same membrane was reprobed with anti–β-tubulin Ab to ensure equal loading. Representative data of three experiments are shown. ***p < 0.001.

FIGURE 3. CD72c is a poor negative regulator of BCR signaling and B cell activation. Spleen B cells were purified from 8–12-wk-old QM and QM. CD72−/− mice. Fluo-4/AM-loaded (A) or untreated (B) cells were stimulated with 0.2 μg/ml NP-BSA. Intracellular free calcium ion level was measured by flow cytometry (A). The arrowhead indicates the time point when NP-BSA was added. Alternatively, total cell lysates were analyzed for phosphorylation of ERK by Western blotting (B). The same membrane was reprobed with anti–β-tubulin Ab to ensure equal loading. Representative data of three experiments are shown. (C) Purified spleen B cells from B6 or B6.CD72−/− mice were labeled with CFSE and cultured with indicated reagents for 72 h. CFSE fluorescence was analyzed by flow cytometry. The percentages of proliferated cells are indicated (left panel). Mean ± SD of triplicate is shown (right panel). Data are representative of three independent experiments. (D) CD72 expression in indicated BAL17 transfectants were analyzed by flow cytometry using anti-CD72 Abs K10.6 reactive to CD72a and CD72b and JY/93 reactive to CD72b and CD72c. Mean fluorescence intensity (MFI) is indicated. Unstained cells were used as negative controls (shaded histograms). Fluo-4/AM–loaded (E) or untreated (F) BAL17 transfectants were stimulated with 10 μg/ml anti-IgM Ab. Calcium ion concentration was analyzed by flow cytometry (E). The arrowhead indicates the time point when anti-IgM Ab was added. Representative data of five experiments are shown. Total cell lysates were analyzed for phosphorylation of ERK by Western blotting (F). The same membrane was reprobed with anti–β-tubulin Ab to ensure equal loading. Representative data of three experiments are shown. (G) Total cell lysates of purified spleen B cells from B6 and B6.CD72−/− mice were immunoprecipitated (IP) with anti-CD72 or control Ab and analyzed by Western blotting using anti-IgM and anti-CD72 Abs. Representative data of three experiments are shown. ***p < 0.001.

in wild-type B6 B cells (Fig. 4B). Thus, CD72 appears to efficiently regulate BCR ligation–induced ERK phosphorylation but not calcium signaling in agreement with our results in QM. CD72−/− B cells and BAL17 transfectants (Fig. 3). Proliferative response to CPG and anti-CD40 Ab was augmented in B6.CD72−/− B cells compared with wild-type B6 B cells (Fig. 4C), as is the case for B6.CD72−/− B cells. Thus, signaling and proliferative properties of B6.CD72−/− B cells are similar to those of CD72−/−–carrying B cells.

We then bred Cd72−/− mice with B6/lpr mice and analyzed 6-mo-old female Cd72−/− B6/lpr mice. These mice showed severe splenomegaly (Fig. 4D) and lymphadenopathy (data not shown) and marked expansion of lpr T cells in spleen, LNs, and peritoneal cavity (peritoneal exudate cells [PEC]) (Tables II, III), whereas expansion of lpr T cells is mild in B6/lpr mice. As is the case for B6.CD72−/−/lpr mice, percentages of T cells and B cells were increased and decreased, respectively, in Cd72−/−/B6/lpr mice (Table II). In contrast, Cd72−/− mice showed mild splenomegaly but no distorted proportions of T and B cells. Thus, CD72 deficiency induces marked splenomegaly synergistically with the Faslpr gene and accelerates expansion of lpr T cells.

Although the serum IgG level in Cd72−/− B6 and Cd72−/− B6/lpr mice at 6 mo of age were comparable to that in age-matched Cd72−/−/B6 mice, the high titer of anti-chromatin IgG was produced in both Cd72−/− and Cd72−/− B6/lpr mice (Fig. 4E). Although the titers of anti-dsDNA and anti-ssDNA IgG were significantly increased in Cd72−/− B6 mice compared with Cd72−/− B6 mice, the titers of these autoantibodies were markedly higher in Cd72−/− B6/lpr mice than in Cd72−/− B6 mice (Fig. 4E), suggesting that CD72 deficiency induces production of a large amount of anti-DNA Abs in the presence of the Faslpr gene. Histopathological analysis revealed development of glomerulonephritis with immune complex deposition (Fig. 4F, 4G) and cell infiltration in lung (Fig. 4H) in Cd72−/− B6 mice, which are consistent with the previous report (35). Cd72−/− B6/lpr mice developed more severe glomerulonephritis and cell infiltration in lung and liver than Cd72−/− B6 or B6/lpr mice, suggesting that CD72 deficiency induces development of autoimmune glomeru-
Figure 4. Severe autoimmune disease in Cd72−/− B6/lpr mice. (A and B) Spleen B cells were purified from 8–12-wk-old B6 and Cd72−/− B6 mice. Total cell lysates were analyzed for phosphorylation of ERK by Western blotting (A). The same membrane was reprobed with anti-β-tubulin Ab to ensure equal loading. The intensity of the protein bands was quantified, and the relative amounts of phosphorylated ERK and β-tubulin are indicated. Representative data of three experiments are shown. Alternatively, Fluo-4/AM–loaded cells were stimulated with 10 μg/ml anti-IgM Ab (B). Intracellular free calcium ion level was measured by flow cytometry. The arrowhead indicates the time point when anti-IgM Ab was added. (C) Purified B cells from B6 and Cd72−/− B6 mice were labeled with CFSE and cultured with indicated reagents for 72 h. CFSE fluorescence was analyzed by (Figure legend continues)
lonephritis and cell infiltration in lung and liver synergistically with the Faslpr gene.

**Discussion**

Autoimmune disease caused by Faslpr depends on the genetic background of mouse strains. In this study, we demonstrate that introduction of the MRL-derived chromosomal interval containing Cd72− into B6 mice did not cause any disease but markedly enhanced severity of autoimmune disease in B6/lpr mice. This result clearly demonstrates that this locus contains a modifier gene that regulates Faslpr-induced autoimmune disease. Conversely, introduction of the B6-derived interval containing Cd72c reduced the severity of the disease in MRL/lpr mice further support the crucial role of this locus in regulation of Faslpr-induced autoimmune disease. We also demonstrated that Cd72c is hypofunctional in regulating BCR signaling and B cell activation and that Cd72c deficiency induces severe autoimmune disease in the presence of Faslpr. Thus, in B6.CD72c/lpr mice, the hypofunctional Cd72c allele but not other genes in the MRL-derived chromosomal interval appears to be responsible for induction of severe autoimmune disease, and Cd72c is a modifier gene that regulates Faslpr-induced autoimmune disease.

Our finding on the role of Cd72c in development of autoimmune disease is also supported by the finding by Oishi et al. (36). They introduced the MRL-derived chromosomal interval containing the B6-derived interval containing Cd72c. The Cd72c-containing BAC but not the mutant BAC markedly reduced BCR signaling and severity of the autoimmune disease in MRL/lpr mice, clearly demonstrating distinct functional activity of Cd72c and its role in development of autoimmune disease in MRL/lpr mice, in agreement with our finding. Previously, Li et al. (35) demonstrated that Cd72c−/− mice spontaneously develop autoimmune manifestations including glomerulonephritis and inflammatory infiltration of the lung and salivary glands at 1 y of age, and we confirmed this finding in the independently established Cd72−/− mouse line (Fig. 4). Thus, Cd72c deficiency but not Cd72c causes mild lupus-like disease by itself. Cd72c may not cause autoimmune disease by itself as it probably retains its regulatory activity to some extent. Thus, a hypofunctional allele of a gene that is crucial for preventing autoimmune disease can play a role as a modifier gene.

An old study demonstrated that the Faslpr locus induces autoimmune disease in mice with AKR but not C3H or B6 backgrounds (8). Because AKR as well as MRL carries Cd72c, Cd72c may be a modifier gene involved in the development of autoimmune disease in AKR/lpr as well as MRL/lpr mice. In human, mutations of Fas cause autoimmune lymphoproliferative syndrome (ALPS), in which penetrance is variable among families (6, 7, 37). As there is a functional difference between human Cd72 haplotypes (38, 39), Cd72 polymorphism may play a crucial role in the regulation of penetrance and disease manifestations in ALPS. Modifier genes are extensively studied in various diseases including cystic fibrosis, arrhythmia, and cancer because modifier genes extensively regulate penetrance, severity, and manifestations of these diseases (1–3). Also, modifier genes can be a good target of therapy and prevention if it is difficult to correct the defect caused by disease-causing mutations. However, little is known about modifier genes that regulate autoimmune diseases. The Yaa gene may be another modifier gene that regulates autoimmune diseases. The Yaa gene may be another modifier gene that regulates autoimmune diseases because it is required for development of autoimmune disease in BXSB mice but does not induce autoimmune disease by itself in the B6 background (40), although Yaa is naturally found only in BXSB mice. As most cases of autoimmune diseases appear to involve multiple genes, all of which contribute to a minor component (41), it may not be straightforward to dis-

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Table II. Flow cytometry analysis of spleen cells from B6, Cd72−/− B6, B6/lpr, and Cd72−/− B6/lpr mice

<table>
<thead>
<tr>
<th>Cell Population</th>
<th>B6</th>
<th>Cd72−/− B6</th>
<th>B6/lpr</th>
<th>Cd72−/− B6/lpr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number (×10^6)</td>
<td>98.8 ± 9.3</td>
<td>160.2 ± 15.4</td>
<td>121.6 ± 12.4</td>
<td>308.8 ± 92.8</td>
</tr>
<tr>
<td>Phenotype (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B220+CD3 (B cells)</td>
<td>45.6 ± 2.2</td>
<td>40.0 ± 2.4</td>
<td>55.1 ± 1.3</td>
<td>21.6 ± 3.6***</td>
</tr>
<tr>
<td>(× 10^6)</td>
<td>(44.5 ± 3.9)</td>
<td>(63.2 ± 6.2)</td>
<td>(66.9 ± 6.5)</td>
<td>(54.4 ± 6.6)</td>
</tr>
<tr>
<td>CD3+ B220− (T cells)</td>
<td>41.4 ± 2.7</td>
<td>41.7 ± 1.2</td>
<td>19.4 ± 1.2</td>
<td>31.0 ± 4.2</td>
</tr>
<tr>
<td>(× 10^6)</td>
<td>(41.3 ± 5.3)</td>
<td>(66.3 ± 5.6)</td>
<td>(23.8 ± 3.6)</td>
<td>(108.7 ± 49.6)</td>
</tr>
<tr>
<td>B220−CD3−</td>
<td>12.1 ± 1.4</td>
<td>16.3 ± 2.4</td>
<td>8.0 ± 1.0</td>
<td>16.0 ± 2.5</td>
</tr>
<tr>
<td>(× 10^6)</td>
<td>(12.0 ± 1.6)</td>
<td>(27.3 ± 5.5)</td>
<td>(9.6 ± 1.2)</td>
<td>(41.9 ± 4.9)**</td>
</tr>
<tr>
<td>B220−CD3+ (lpr T cells)</td>
<td>0.9 ± 0.1</td>
<td>2.0 ± 0.5</td>
<td>17.5 ± 1.2</td>
<td>31.3 ± 3.7**</td>
</tr>
<tr>
<td>(× 10^6)</td>
<td>(0.9 ± 0.2)</td>
<td>(3.4 ± 1.0)</td>
<td>(21.3 ± 2.6)</td>
<td>(103.8 ± 40.5)**</td>
</tr>
</tbody>
</table>

| Phenotype of B220+ B cells (%) |  | | | |
| CD21+CD23+ (FO B cells) | 76.1 ± 2.1 | 52.6 ± 3.1* | 46.3 ± 1.4 | 15.8 ± 5.0*** |
| CD21+CD23− (MZ B cells) | 11.0 ± 0.9 | 7.2 ± 0.7* | 10.8 ± 0.9 | 0.6 ± 0.3*** |

Data were obtained from 6-mo-old mice and are expressed as mean ± SEM (n = 5 to 6). Statistical significance was calculated between B6 and Cd72−/− B6 mice and between B6/lpr and Cd72−/− B6/lpr mice.

*Percentages of cells expressing the indicated surface markers in lymphocyte-gated cells.

**Absolute cell numbers are indicated in parentheses.

***p < 0.05, **p < 0.01, *p < 0.001.

FO, Follicular; MZ, marginal zone.
tistinguish modifier genes from disease-causing genes in autoimmune diseases, except for the cases in which a single gene plays a dominant role, such as patients with ALPS and MRL/lpr mice.

In this study, the autoimmune disease in B6.CD72c/lpr mice is less severe than that in MRL/lpr mice, indicating involvement of other MRL-derived genes in development of the severe disease. This is consistent with the previous findings on the association of other genetic loci such as the Opn (20) and FcyRIIB loci (42, 43) with development of autoimmune disease in MRL/lpr mice. Thus, multiple genes including Fas (44) and CD72 are involved in development of severe autoimmune disease in MRL/lpr mice. Lack of these genes other than Fas and CD72 may explain why AKR/lpr develops milder autoimmune disease than MRL/lpr does. Identification of the modifier genes in the MRL background that are involved in the autoimmune disease enables us to study how these genes interact with each other and ultimately induce the autoimmune disease.

It is already well established that CD72 is a negative regulator of BCR signaling (12–16). Expression of CD72 negatively regulates both calcium signaling and ERK phosphorylation induced by BCR ligation in BAL17 cells (Fig. 3). In contrast, CD72−/− B cells show augmented ERK phosphorylation but no alteration in calcium signaling induced by treatment with anti-IgM Ab (Fig. 4A, 4B). However, a previous study demonstrated that BCR ligation-induced calcium response is enhanced in CD72−/− B cells (15, 16). Thus, CD72-mediated regulation of BCR signaling depends on experimental conditions. In the current study, we demonstrated that CD72 is hypofunctional. This property of CD72 may cause enhanced B cell activation, which may be involved in development of autoimmune disease through augmented autostimulatory production. The hypofunctional property of CD72 may not be due to its expression efficiency on the cell surface as surface expression level of CD72 in B6.CD72−/− B cells appears to be equivalent to that of CD72 in B6 B cells, although it is not proven if the anti-CD72 Ab used for measuring CD72 expression level detects CD72b and CD72c equally (Supplemental Fig. 3). In contrast, CD72 coprecipitates BCR less efficiently than CD72a (Fig. 3G), suggesting that interaction of CD72 with BCR is weaker than that of CD72a. As interaction and colocalization of inhibitory coreceptors including FcyRIIB with BCR is crucial for their inhibitory activity (44, 45), less efficient interaction of CD72 with BCR may reduce its regulatory activity on BCR signaling. CD72 contains several amino acid substitutions and a 7-aa deletion in the extracellular region compared with CD72a or CD72b, whereas the cytoplasmic region of CD72a is identical to that of CD72c or CD72b (18, 19). Alterations in the extracellular region of CD72 may change its association with BCR or binding to its ligands, leading to reduction in its colocalization with BCR either directly or indirectly. Although CD100 was reported to be a ligand of CD72 (46), there might be other ligands. Thus, full elucidation of the interaction of CD72 with BCR and ligands may be crucial to understand the defect in signaling function of CD72a and its role in development of autoimmune disease.

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Disclosures

The authors have no financial conflicts of interest.

References

membrane protein CD72 binds to and is an in vivo substrate of the protein tyrosine phosphatase SHP-1. *Cancer Res.* 8: 1009–1017.


SUPPLEMENTAL FIGURE 1: Schematic diagrams of the genomic structure surrounding \textit{Cd72} gene in the B6.CD72\(^c\) (A) and MRL.CD72\(^b\)/lpr (B) congenic strains, respectively. Black and white bars represent the B6-derived and MRL-derived genomes as indicated. Grey bars represent the regions of recombination between the MRL and B6 genomes. The microsatellite markers used to delineate the boundaries of the intervals are indicated. Positions in cM from the centromere are indicated in parentheses.
SUPPLEMENTAL FIGURE 2: Generation of Cd72⁻/⁻ mice. (A). Targeting strategy. Structures of the wild-type Cd72 locus (top), Cd72 targeting construct (middle) and the targeted Cd72 locus (bottom) are shown. Black boxes and shaded triangles represent Cd72 exons and LoxP site, respectively. The probe for Southern blotting, the neomycin-resistance (neo) and thymidine kinase (tk) genes are indicated. (B). Southern blot analysis of ES cell clones. Hind III-digested genomic DNA from ES cell clones #4 and #150 are shown. The 21 kb and the 8 kb fragments derived from the wild-type and targeting Cd72 alleles, respectively, are indicated. (C). Flow cytometry analysis. Splenocytes from Cd72⁺/+ (left) and Cd72⁻/⁻ (right) mice were stained with anti-CD72 and anti-B220 Abs, and lymphocyte-gated cells were analyzed. (D). Detection of CD72 expression in spleen cells by Western Blot analysis. Total lysates of spleen cells from wild type B6 (Cd72⁺/+ ) and Cd72⁻/⁻ mice were immunoprecipitated with anti-CD72 Ab (K10.6) and analyzed by Western blotting using polyclonal rabbit anti-mouse CD72 Ab.
SUPPLEMENTAL FIGURE 3: The expression level of CD72c does not differ from that of CD72b. Spleen cells from B6 and B6.CD72c mice were stained with anti-B220 and anti-CD72 Ab (JY/93) that recognizes both CD72b and CD72c. CD72 expression of B220+ gated cells were analyzed by flow cytometry. MFI were indicated. Cells stained with anti-B220 Ab alone were used as negative controls (shaded histograms).