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*J Immunol* 2012; 189:5434-5441; Prepublished online 29 October 2012;
doi: 10.4049/jimmunol.1201621
http://www.jimmunol.org/content/189/11/5434

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Absence of CD59 Exacerbates Systemic Autoimmunity in MRL/lpr Mice

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CD59 is a GPI-anchored membrane regulator of complement expressed on blood cells as well as peripheral tissues. It protects host cells from complement injury by inhibiting formation of the membrane attack complex. Recent studies in mice have suggested also a role of CD59 in T cell immune response that was mechanistically independent of complement. In the present study, we investigated the function of CD59 in the MRL/lpr model of murine lupus. We backcrossed the Cd59a knockout (Cd59a<sup>-/-</sup>) mouse onto the MRL/lpr background and compared Cd59a<sup>+/-</sup>-MRL/lpr and Cd59a<sup>-/-</sup>-MRL/lpr littermates for the development of systemic autoimmunity. We found that Cd59a deficiency significantly exacerbated the skin disease and lymphoproliferation characteristic of MRL/lpr mice. It also increased autoantibody titers and caused a higher level of proteinuria in male MRL/lpr mice. Bone marrow transfer experiments indicated that Cd59a expression on both bone marrow–derived cells and peripheral tissues played a role in lymphoproliferation, whereas the skin disease phenotype is determined mainly by local Cd59a expression. Importantly, C3 gene deletion or C5 neutralization with a blocking mAb in Cd59a<sup>-/-</sup>-MRL/lpr mice did not rescue the proautoimmune phenotype associated with Cd59a deficiency. These results together suggest that Cd59a inhibits systemic autoimmunity in MRL/lpr mice through a complement-independent mechanism. The Journal of Immunology, 2012, 189: 5434–5441.

Abstract

Systemic lupus erythematosus (SLE) is an autoimmune disorder characterized by high levels of autoantibody production and multiorgan tissue damage including kidney and skin involvement (1, 2). The complement system has been shown to play an important but paradoxical role in the pathogenesis of SLE. On the one hand, genetic deficiencies of classical pathway components such as C1q, C2, and C4 strongly increase the risk of developing a monogenic form of SLE, suggesting an essential role of the classical pathway complement in preventing the onset of disease, possibly owing to their role in clearance of apoptotic cells and autoantigens. On the other hand, autoantibody- and immune complex–mediated end organ injury is considered to involve complement activation as an effector pathway (3). The role of complement as a double-edged sword in SLE pathogenesis and development has also been demonstrated in transgenic mouse studies. Mice lacking C1q or C4, much as humans with similar genetic deficiencies, are predisposed to develop an SLE-like autoimmune phenotype (4–7). In contrast, deletion of the key alternative pathway complement proteins factor B or factor D ameliorated aspects of the autoimmune disease phenotype of MRL/lpr mice (8, 9). Deletion of C3 did not offer much protection in MRL/lpr mice, possibly reflecting a zero sum effect of C3 in contributing to inflammation as well as to immune complex solubilization and clearance (10).

Under physiological conditions, host tissues are protected from complement-mediated autologous injury because of the presence of a number of cell membrane–linked and fluid phase complement regulatory proteins (11, 12). Two central membrane-bound complement regulators in mammals are the decay-accelerating factor (DAF) and CD59, both of which attach to the cell surface via a GPI anchor. DAF inhibits complement activation by preventing the formation and accelerating the decay of C3 and C5 convertases, whereas CD59 inhibits the formation of the membrane attack complex (MAC) and thus serves as a key regulator of the terminal complement pathway on host cells (12). Additionally, both DAF and CD59 have been implicated in T cell–mediated immune responses that were either complement-dependent or complement-independent (13–16). It has been well documented that mutations in membrane or fluid phase complement regulators in humans are associated with alternative pathway complement-mediated rare, but potentially life-threatening, diseases such as paroxysmal nocturnal hemoglobinuria, C3 glomerulopathy, and atypical hemolytic uremic syndrome (17–19). The role of complement regulatory proteins in the pathogenesis and manifestation of human systemic autoimmune diseases in general, and SLE in particular, has not been well studied.

Using the MRL/lpr murine model of SLE, we previously have obtained evidence for a role of DAF in mitigating SLE development in ways that were both complement-dependent and complement-independent (13). We showed that lack of DAF exacerbated the autoimmune manifestations in MRL/lpr mice by causing increased lymphoproliferation, antichromatin autoantibody production, and dermatitis (20). In the present study, we have investigated the...
role of CD59 in the MRL/lpr model of murine SLE. Unlike humans, the mouse has two Cd59 genes (Cd59a and Cd59b) that are located in tandem on chromosome 2 (21, 22). Both genes encode functionally active GPI-anchored proteins but only the Cd59a gene, similar to human Cd59, is widely expressed across different tissues whereas Cd59b expression is restricted to the mouse testis (23). Thus, Cd59a is considered to be functionally more representative of human Cd59. We backcrossed the Cd59a-deficient mouse onto the MRL/lpr background. We found that Cd59a deficiency significantly exacerbated several aspects of the autoimmune diseases phenotype of MRL/lpr mice, including lymphoproliferation, dermatitis, autoantibody production, and nephritis. Interestingly, the effect of Cd59a was determined to be independent of C3 and Cs. Thus, our data suggest an activity of Cd59 in regulating SLE-like systemic autoimmunity through a novel and complement-independent mechanism.

Materials and Methods

Mice

The generation of the Cd59a knockout (Cd59a<sup>-/-</sup>) mouse has been described previously (24). Cd59a<sup>-/-</sup> mice were crossed with MRL/lpr-lgh<sup>lpr</sup> mice (MRL/lpr mice contain on the Ig<sup>H</sup> allele maintained in our animal colony) for a total of nine generations. Nine-time-backcrossed Cd59a<sup>-/-</sup>-MRL/lpr mice were then intercrossed to derive Cd59a<sup>+/+</sup>-MRL/lpr and Cd59a<sup>-/-</sup>-MRL/lpr mice as littermates. Cd59a<sup>-/-</sup> C3<sup>-/-</sup>-MRL/lpr mice as well as Cd59a<sup>-/-</sup>-MRL/lpr mice were obtained by crossing Cd59a<sup>-/-</sup>-MRL/lpr mice with C3<sup>-/-</sup>-MRL/lpr mice as previously described (10). The generation of Daf<sup>+/+</sup> Cry<sup>+/+</sup> mice mean age 129F1 and 129F1 background was described previously (25). The Cd59a genotypa was screened by FACS analysis of erythrocytes as described previously (24). C3 genotyping was performed by PCR of tail DNA (13). Mice were monitored for autoimmune disease until they were 5 mo old, at which time they were sacrificed for pathological evaluation. Mice were kept in a specific pathogen-free barrier facility, and all animal experiments were approved by the Institutional Animal Care and Use Committee of the University of Pennsylvania.

Generation of bone marrow chimera mice

Bone marrow (BM) chimera mice were generated between male Cd59a<sup>+/+</sup>-MRL/lpr and Cd59a<sup>-/-</sup>-MRL/lpr mice. BM cells were flushed out from the bones (femur and tibia) of donor mice. After filtration through nylon mesh and clearing of erythrocytes with RBC lysing buffer (ACK buffer), the single-cell suspension was depleted of mature T and B cells by incubating with anti-CD4, CD8, CD19, and CD90 Abs conjugated to magnetic microbeads (Miltenyi Biotec, Auburn, CA), followed by processing with a fully automated ClinMACS device (Miltenyi Biotec) equipped with TS separation columns. Recipient mice were lethally irradiated with two doses of 525 rads spaced 3 h apart. Irradiated recipient mice then received T/B cell-depleted donor mouse BM cells (1 × 10<sup>5</sup> cells/mouse) through the tail vein. Repopulation of the immune system was monitored by flow cytometric analysis of the blood using rat anti-mouse Cd59a. In the chimeric mice, >95% of the T cells, B cells, and myeloid cells were derived from donor bone marrow. Mice were studied for immunity for 5 mo after BM transfer.

Assessment of dermatitis

Mice were inspected monthly for the development of dermatitis in the usual body site, and the age at which open skin lesions developed was recorded and lesion size was measured with a ruler.

ELISA for autoantibodies and their isotypes

Serum was collected by tail vein bleeding at 3, 4, and 5 mo of age and frozen at -20˚C until use. Sandwich ELISA was used for determining the titers of Abs. For total serum IgM, IgG, and IgG2a, plates were coated with the appropriate capture Ab. Diluted sera, as well as serially diluted IgM, IgG, and IgG2a standards, were added to the plates and allowed to bind overnight. The plate was incubated with biotin-conjugated anti-mouse IgM, IgG, and IgG2a Abs (Jackson ImmunoResearch Laboratories, West Grove, PA) for 2 h at 4˚C. Avidin-alkaline phosphatase (Sigma-Aldrich, St. Louis, MO) was added, followed by para-nitrophenylphosphate (Sigma-Aldrich) for color development. OD<sub>405</sub> was measured using a microplate reader (Molecular Devices, Sunnyvale, CA). Similar procedures were used for determining Ag-specific autoantibodies, except that the plates were coated with the target Ag, chromatin, or dsDNA. Quantification was achieved with either a standard curve (total IgM, IgG, IgG2a) or a positive serum sample from a 5-mo-old MRL/lpr mouse as an internal standard (Ag-specific autoantibodies) for interplate comparison. Ig concentrations or relative OD<sub>405</sub> values for serum from each animal were plotted individually.

Assessment of nephritis

Urine samples were collected in metabolic cages atmonthly intervals starting at 3 mo until sacrifice. Urinary albumin concentration was measured by a mouse albumin ELISA kit (Bethyl Laboratories, Montgomery, TX) and normalized to urinary creatinine. At the time of sacrifice, one kidney was fixed in 10% buffered formalin and processed for paraffin embedding and sectioning, followed by H&E staining and histological evaluation. The other kidney was frozen in OCT medium and processed for immunofluorescence staining of IgG and C3 with fluorescent isothiocyanate-conjugated goat anti-mouse IgG and C3 F(ab')<sub>2</sub> fragments (used at 1:75 for anti-IgG and 1:500 for anti-C3; MP Biomedicals, Durham, NC). The presence and severity of nephritis was determined as previously described (10). A blinded observer (M.P. Madaiio) evaluated and scored independently the severity of glomerular and interstitial nephritis (0–4 scale) by light microscopy (26). Similarly, the presence of glomerular or tubular basement membrane deposits of IgG and C3 was graded on a 0–3 scale by immunofluorescence microscopy (27). Multiple sections at a minimum of two different levels were observed. Each section typically involved evaluation of >25 glomeruli, >10 blood vessels, and the interstitium contained within two to three longitudinal sections of kidney.

Analysis of lymphoproliferation

At the time of sacrifice, spleen and cervical, axillary, inguinal, and mesenteric lymph nodes (LNs) were weighed, meshed, and cleared of erythrocytes by ACK buffer. After the spleen and LN cells were counted by cell counter (Beckman Coulter, Fullerton, CA), the cell suspension (1.5 × 10<sup>6</sup> cells) was incubated with Abs to the following cell surface markers: Thy1.2-PE, CD4-PE, CD8-PE, B220-FITC, CD19-FITC, and CD1-FITC (BD Pharmingen, San Diego, CA). Flow cytometry analysis was performed by using FACScan with CellQuest data acquisition software (Becton Dickinson Immunocytometry Systems, San Jose, CA).

Analysis of expression of Cd59a

Cd59a expression on erythrocytes or lymphocytes from spleen, lymph nodes, and thymus was evaluated by flow cytometry using FITC-conjugated anti-mouse Cd59a mAb (Hyctul Biotech, Plymouth Meeting, PA). Cells were stained for a panel of surface markers including CD3, CD4, CD8, B220, CD19, and Thy1.2 to identify relevant cell populations. Fluorescence-labeled Abs against the cell surface markers were from BD Pharmingen.

Anti-C5 mAb treatment

The source and preparation of mouse anti-mouse C5 mAb (BBS.1) was described previously (14). An isotype control mAb (MOPC21, IgG1, lymphohilized protein) was from Sigma-Aldrich. BBS.1 or MOPC21 mAbs (1 mg/kg i.p.) were injected twice weekly for 3 mo (from 2 to 5 mo old).

Hemolytic assays

Hemolytic assay was performed as described (28). Briefly, erythrocytes from Daf<sup>+/+</sup> Cry<sup>+/+</sup> mice (25) were incubated (37˚C, 30 min) with 50% serum from anti-mouse C5 mAb or isotype control mAb-treated Cd59a<sup>-/-</sup>-MRL/lpr mice (taken 2 wk after twice weekly mAb treatment) in the presence of 5 μM recombiant mouse factor H short consensus repeat 19–20 (28). At the end of the incubation period, cold EDTA-PBS was added to stop the reaction. Samples were centrifuged and the supernatant OD values were measured at 405 nm. Percentage hemolysis was calculated by dividing the OD<sub>405</sub> value with that of a sample in which total hemolysis was induced by hypotonic shock (28).

Statistical analysis

Data were analyzed by a Student t test (for normally distributed data), Mann–Whitney U test (for nonparametric data), or a Fisher exact test (for incidence of dermatitis) as specified in the text, and significant difference is defined as p < 0.05.

Results

To assess whether Cd59a plays a role in the pathogenesis of lupus-like disease in mice, we backcrossed a Cd59a<sup>-/-</sup> mouse (originally on a mixed C57BL/6·129/SvEv background) (24) onto the MRL/lpr genetic background for a total of nine generations. Ninth generation
backcrossed CD59a<sup>+/−</sup>-MRL/lpr mice were then intercrossed to obtain CD59a<sup>+/−</sup>-MRL/lpr and CD59a<sup>+/+</sup>-MRL/lpr littermates. In total, we studied 24 CD59a<sup>+/−</sup>-MRL/lpr mice (16 males and 8 females) and 24 CD59a<sup>+/+</sup>-MRL/lpr mice (14 males and 10 females). These mice were monitored for autoimmune disease development until 5 mo of age.

MRL/lpr mice have a mutation in the Fas ligand, leading to impaired apoptosis of lymphocytes (29). They spontaneously develop splenomegaly and lymphadenopathy owing to accumulation of lymphocytes expressing an activated phenotype in these organs (30). This lymphoproliferation affects all lymphocytes subtypes but is mostly composed of CD4<sup>+</sup>CD8<sup>−</sup> aberrant αβ T cells that are B220<sup>+</sup>/Thy1.2<sup>+</sup> (31). Although the role of these aberrant T cells (MRL/lpr mice. Twenty-four in total, we studied 24 (16 males and 8 females) and 24 CD59a<sup>+/+</sup>-MRL/lpr mice (14 males and 10 females). This increase in the aberrant T cell population was mirrored by corresponding decreases in normal T cells of various developmental stages, including CD4<sup>+</sup> and CD8<sup>+</sup> T cells (Fig. 1D) as well as other cell populations (e.g., B cells: B220<sup>+</sup>/CD19<sup>+</sup> and IgM<sup>+</sup>/CD21<sup>+</sup>; data not shown). There were also significant differences between CD59a<sup>+/−</sup>-MRL/lpr and CD59a<sup>+/−</sup>-MRL/lpr mice in the total number of LN and spleen cells, as well as various cell subsets (CD4<sup>+</sup> or CD8<sup>+</sup> T cells, aberrant B220<sup>+</sup>/Thy1.2<sup>+</sup> T cells in the LNs, aberrant B220<sup>+</sup>/Thy1.2<sup>+</sup> T cells, B220<sup>+</sup>/CD19<sup>+</sup> and IgM<sup>+</sup>/CD21<sup>+</sup> B cells in the spleen) (Fig. 1E, 1F).

Starting at 3 mo of age, both male and female CD59a<sup>+/−</sup>-MRL/lpr mice developed severe autoimmune dermatitis, which reached an incidence of ~50% at the time of sacrifice. The wild-type CD59a<sup>+/+</sup>-MRL/lpr cohort showed only a gradual onset of very mild skin disease (Fig. 2). Thus, 5 of 16 male CD59a<sup>+/−</sup>-MRL/lpr mice at 3 mo of age, and 11 of 16 at 5 mo of age, developed severe skin disease, whereas only 1 male of the 24 CD59a<sup>+/+</sup>-MRL/lpr mice was found to have a small open skin lesion at 5 mo of age. Interestingly, susceptibility to skin disease development in CD59a<sup>+/−</sup>-MRL/lpr mice had a gender bias toward males. One third of male CD59a<sup>+/−</sup>-MRL/lpr mice already had skin disease at 3 mo of age but only one of eight female CD59a<sup>+/−</sup>-MRL/lpr mice developed skin disease at 4 mo of age (Fig. 2).

To further examine the immunological changes in CD59a<sup>+/−</sup>-MRL/lpr mice, the level and nature of serum Ig's and autoantibodies were evaluated at 5 mo. We found that serum levels of total

**FIGURE 1.** CD59a deficiency increases lymphoproliferation in MRL/lpr mice. CD59a<sup>+/−</sup>-MRL/lpr (CD59a<sup>−/−</sup>) mice had significantly larger spleens (A) and lymph nodes (B) than did CD59a<sup>+/+</sup>-MRL/lpr (CD59a<sup>+/+</sup>) mice. Flow cytometry analysis showed that CD59a<sup>+/−</sup>-MRL/lpr mouse lymph nodes contained a higher percentage of aberrant B220<sup>+</sup>/Thy1.2<sup>+</sup> T cells (C) and a lower percentage of combined single-positive (CD4<sup>+</sup> or CD8<sup>+</sup>) T cells (D). (E) Cellularity of LNs in 5-mo-old CD59a<sup>+/−</sup>-MRL/lpr and CD59a<sup>+/+</sup>-MRL/lpr mice. (F) Cellularity of spleens in 5-mo-old CD59a<sup>+/−</sup>-MRL/lpr and CD59a<sup>+/+</sup>-MRL/lpr mice. Twenty-four CD59a<sup>+/−</sup>-MRL/lpr mice (16 males and 8 females) and 24 CD59a<sup>+/+</sup>-MRL/lpr mice (14 males and 10 females) were used in (A)–(F). Each datum point in (A)–(D) represents a mouse, and cell numbers in (E) and (F) are averaged (mean ± SE). *p < 0.01, **p < 0.05. Student t test.
IgG and IgM, as well as antichromatin autoantibody titers, were significantly elevated in male Cd59a⁻/⁻-MRL/lpr mice compared with male Cd59a⁺/+⁻-MRL/lpr mice (Fig. 3). Significant increases, however, were not observed in the female Cd59a⁻/⁻-MRL/lpr group. In fact, total IgG levels in female Cd59a⁻/⁻-MRL/lpr mice were actually lower than those of female Cd59a⁺/+⁻-MRL/lpr mice. There was no significant difference in the titers of serum of mouse (disease and of an age-matched mouse at 5 mo of age (Fig. 4A). We found that in general CD59a expression deficiency, we used these disease features as our readouts for this experiment. By using CD59a expression as a measurement, we determined that >95% of blood cells were derived from donor BM (data not shown). We found that in general CD59a expression on BM-derived cells as well as peripheral tissues was important for regulating the autoimmunity phenotype in MRL/lpr mice, we generated BM chimera mice between male Cd59a⁻/⁻- and Cd59a⁺/+⁻-MRL/lpr mice. Because increased lymphoproliferation and development of skin disease were the more striking phenotypes associated with CD59a deficiency, we used these disease features as our readouts for this experiment. By using CD59a expression as a measurement, we determined that >95% of blood cells were derived from donor BM (data not shown). We found that in general CD59a expression on BM-derived cells as well as peripheral tissues had an impact on lymphoproliferation (Fig. 5A, 5B). Thus, chimeric mice generated using Cd59a⁻/⁻-MRL/lpr mice as BM donors had greater lymphoproliferation than did those using Cd59a⁺/+⁻-MRL/lpr as BM cell donors. However, peripheral CD59a expression also affected the degree of lymphoproliferation, as for a given BM cell donor, Cd59a⁻/⁻-MRL/lpr recipients tended to have smaller spleens and lymph nodes (Fig. 5A, 5B). For the skin disease phenotype, however, we found that CD59a expression on peripheral tissues clearly played a dominant role. Regardless of the donor BM cell genotype, chimeric mice generated using Cd59a⁻/⁻-MRL/lpr mice as recipients developed skin disease with higher incidence and increased severity (Fig. 5C, 5D). Thus, skin disease development in Cd59a⁻/⁻-MRL/lpr mice was mainly exacerbated by Cd59a deficiency on peripheral tissues.

To understand how CD59 protected disease progression in MRL/lpr mice, we investigated the role of complement by breeding Cd59a⁻/⁻-MRL/lpr mice with C3⁻/⁻-MRL/lpr mice and by blocking C5 function with a mAb. From C3⁻/⁻-Cd59a⁻/⁻-MRL/lpr intercrosses, we generated and studied 19 (8 males and 11 females) C3⁻/⁻-Cd59a⁻/⁻-MRL/lpr mice and 17 (10 males and 7 females) C3⁺/-Cd59a⁻/⁻-MRL/lpr mice as littermates. Fig. 6 shows that C3 deficiency did not significantly affect lymphoproliferation in Cd59a⁻/⁻-MRL/lpr mice, nor did it reduce the incidence of skin disease. In fact, female C3⁻/⁻-Cd59a⁻/⁻-MRL/lpr mice had the highest incidence of open skin lesions at 5 mo of age (Fig. 6E). In contrast, C3 deficiency reduced skin disease severity, as the average size of open skin lesions in male and female C3⁻/⁻-Cd59a⁻/⁻-MRL/lpr mice was smaller than that of corresponding C3⁺/-Cd59a⁻/⁻-MRL/lpr littermates (Fig. 6F). C3 gene deletion affected neither autoantibody production nor nephritis severity of Cd59a⁻/⁻-MRL/lpr mice (data not shown). In a further experiment, we treated seven male Cd59a⁻/⁻-MRL/lpr mice with an anti-mouse C5 mAb and another seven male mice with a control mAb. The dosage and frequency of anti-C5 mAb treatment was based on published studies (33), and the effectiveness of the anti-C5 mAb to block C5 function was confirmed by diminished hemolytic activity in the treated Cd59a⁻/⁻-MRL/lpr mice (Fig. 7A). However, we found that anti-C5 mAb treatment had no impact on lymphoproliferation or skin disease development in Cd59a⁻/⁻-MRL/lpr mice (Fig. 7B).

Discussion
Our present results are compatible with a protective role of CD59 in the MRL/lpr model of murine lupus. We found that deficiency of CD59 significantly increased lymphoproliferation and exacerbated skin disease development in MRL/lpr mice. The effect of Cd59a deletion on systemic autoimmunity in MRL/lpr mice...
sex hormones. Many human autoimmune diseases including lupus relate to interactions between Daf1 or plasma C5 levels (data not shown). The gender bias may instead mice were significantly elevated compared with male Cd59a also that male MRL/lpr mice (20) previously demonstrated Cd59a expression on mouse T cells using other methods and they observed increased anti-CD3 Ab-induced proliferation with Cd59a−/− mouse CD4+ T cells. To determine the respective roles of Cd59a on hematopoietic cells and peripheral tissues, we generated BM chimeric mice between Cd59−/−MRL/lpr and Cd59+/−MRL/lpr mice. This experiment revealed that expression of Cd59a on BM-derived cells played an important role in regulating the lymphoproliferation phenotype, whereas peripheral expression of Cd59a is critical in preventing skin disease development. In further experiments, we evaluated whether the effect of Cd59a on autoimmunity in MRL/lpr mice is related to Cd59a working as a terminal complement regulator.

Two separate experimental approaches were used to address this question. First, in a crossbreeding experiment, we deleted the C3 gene from Cd59−/−-MRL/lpr mice. If the exacerbated autoimmunity phenotype was caused by increased MAC formation in the absence of Cd59a, then deletion of C3 in Cd59−/−-MRL/lpr mice might prevent complement activation and MAC formation and rescue the phenotype. Of interest, we found that C3 gene deletion had no impact on lymphoproliferation (Fig. 6A–D), suggesting that the regulatory function of Cd59a on this aspect of autoimmunity in MRL/lpr mice was independent of complement. We also detected no reduction in skin disease incidence by C3 deficiency, one limitation of this experiment is that the C3 gene may play a dual role in regulating the lymphoproliferation phenotype, as suggested by other studies (8, 10). The use of an alternative pathway complement inhibitor in future studies may provide additional and more definitive insight. In this context, it is notable that C3 deficiency alleviated the severity of skin disease in Cd59−/−-MRL/lpr mice. The average size of open skin lesions in C3-deficient mice was significantly smaller than C3-sufficient littersmates at 5 mo of age (Fig. 6F).

Another caveat in interpreting the lack of effect of C3 deficiency on lymphoproliferation and skin disease incidence was that C5 activation could have occurred in the absence of C3, as has been demonstrated in other in vivo settings (39). C3-independent cleavage and activation of C5 by proteases such as thrombin has been referred to as the extrinsic pathway of complement activation (39). If such a pathway is operative in MRL/lpr mice, then the effect of Cd59a deficiency could still have been mediated by increased MAC formation even in the absence of C3. To address this possibility, we adopted a second approach and used a neutralizing mAb, given chronically twice per week, to block C5 function. Importantly, although hemolytic assays clearly confirmed the effectiveness of the mAb in blocking the terminal complement pathway, its use in Cd59−/−-MRL/lpr mice did not affect lymphoproliferation nor did it reduce skin disease incidence or severity (Fig. 7). Although we did not test the involvement of C5 in Cd59a sufficient MRL/lpr mice, the anti-C5 experiment in Cd59−/−-MRL/lpr mice showed that disease exacerbation in Cd59−/−-MRL/lpr mice was MAC-independent. That C3 deficiency, but not anti-C5 mAb treatment, reduced skin disease se-


verity in Cd59<sup>-/-</sup>-MRL/lpr mice also suggested an effect of C3 activation products (C3a and/or C3b/iC3b) that is separate from Cd59a function. The lack of a MAC-mediated effect in Cd59<sup>-/-</sup>-MRL/lpr mice may reflect the fact that there are multiple C3 complement regulators in the mouse, and any consequence of CD59a deficiency may become evident only in the context of an

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FIGURE 4. Effect of CD59a deficiency on renal disease of MRL/lpr mice. Male Cd59a<sup>-/-</sup>-MRL/lpr (Cd59a<sup>-/-</sup>) mice developed significantly increased proteinuria (A) and glomerular/tubular IgG deposition (C) compared with male Cd59a<sup>+/+</sup>-MRL/lpr (Cd59a<sup>+/+</sup>) littermates. **p < 0.05, Mann–Whitney U test. There were no significant difference in glomerular nephritis scores (B) and glomerular/tubular C3 staining (D) between Cd59a<sup>-/-</sup> and Cd59a<sup>+/+</sup>-MRL/lpr mice. Scores for IgG and C3 deposition represent composite scores of glomerular/tubular staining (maximal score 6).

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FIGURE 5. Bone marrow chimera experiment between Cd59a<sup>-/-</sup>-MRL/lpr (Cd59a<sup>-/-</sup>) and Cd59a<sup>+/+</sup>-MRL/lpr (Cd59a<sup>+/+</sup>) mice. Assessment of splenomegaly (A) and lymphadenopathy (B) of the chimeric mice at 5 mo after BM transfer showed a greater degree of lymphoproliferation when the BM donors were Cd59a<sup>-/-</sup>-MRL/lpr mice. However, peripheral Cd59a also had an impact on lymphoproliferation [compare Cd59a<sup>-/-</sup> → Cd59a<sup>+/+</sup> and Cd59a<sup>-/-</sup> → Cd59a<sup>-/-</sup> groups in (A) and Cd59a<sup>-/-</sup> → Cd59a<sup>-/-</sup> and Cd59a<sup>-/-</sup> → Cd59a<sup>+/+</sup> groups in (B)]. In contrast, only peripheral CD59a expression was important for preventing skin disease development in MRL/lpr mice. *p < 0.05, Student t test for (A) and (B). (C) Percentage of mice with visible open skin lesions at 2–5 mo after BM transfer. Chimeras with Cd59a<sup>-/-</sup>-MRL/lpr (Cd59a<sup>-/-</sup>) mice as recipients (filled symbols) appeared to be more prone to develop skin disease than did those with Cd59a<sup>+/+</sup>-MRL/lpr (Cd59a<sup>+/+</sup>) mice as recipients (open symbols). ***p < 0.05 versus Cd59a<sup>-/-</sup> → Cd59a<sup>-/-</sup>. Fisher exact test. Numbers of mice are indicated on the graph. (D) The average size of open skin lesions (mean ± SE) in chimeras at 3–5 mo after BM transfer. Data plotted are only for mice with open skin lesions (numbers indicated above the columns) among the same mice studied in (C). Group b and c mice had clearly less skin disease, as there were fewer than two mice with open skin lesions at any time point. No statistical difference was found between group a and d mice at 4 and 5 mo (n = 3–5, Mann–Whitney U test).
impairment in C3 regulation. Indeed, we previously have found that whereas CD59a−/− mice did not show enhanced susceptibility to renal ischemia reperfusion injury, Daf1−/−CD59a−/− mice had markedly increased sensitivity to renal ischemia reperfusion injury compared with either wild-type or Daf1−/− mice (40).

Several lines of evidence argue against the possibility that 129 mouse strain–derived loci that are closely linked to the Cd59a gene accounted for some or all of the proautoimmune phenotypes observed in Cd59a−/−MRL/lpr mice. First, the mouse Cd59a gene is located on chromosome 2 (21), and most well-defined 129 strain-derived SLE loci are localized to mouse chromosomes 1 and 3 (41, 42). Second, our results are reminiscent of and compatible with a previously demonstrated complement-independent role of CD59a in regulating CD4+ T cell immunity in mAb blocking

**FIGURE 6.** Effect of C3 gene deletion on lymphoproliferation and skin disease development in Cd59a−/−MRL/lpr mice. C3−/−Cd59a−/−MRL/lpr mice and Cd59a−/−MRL/lpr mice were produced as littersates and studied for 5 mo. No difference was seen in splenomegaly (A) and lymphadenopathy (B) between the two genotypes. There was also no difference between C3−/− and C3+/−Cd59a−/−MRL/lpr mice in the percentage of abnormal T cells (C) or single-positive (CD4+ or CD8+) T cells (D) in their lymph nodes. C3 gene deletion did not reduce the incidence of open skin lesions (E) but did reduce open skin lesion size (F) in Cd59a−/−MRL/lpr mice. Numbers of mice for (C) are indicated on the graph. In (E), average lesion size (mean ± SE) was only for mice with open lesions (numbers indicated above the columns) among the same mice studied in (C).

**FIGURE 7.** Lack of an effect of C5 blockade with mAb on lymphoproliferation and skin disease development in Cd59a−/−MRL mice. (A) Hemolytic activities of sera from Cd59a−/−MRL/lpr mice treated with an anti-C5 (α-C5, n = 7) or control (Con, n = 7) mAb. Spleen and lymph node weights (B), percentage of mice with open skin lesions (C), and average open skin lesion size (D) were not significantly different between Cd59a−/−MRL mice treated with anti-C5 (n = 7) or control mAb (n = 7). Average size of open skin lesions (mean ± SE) was only for mice with open skin lesions (numbers indicated above the columns) among the same mice studied in (C). *p < 0.0001, Student t test.
experiments in vitro and in a murine model of recombinant vaccinia virus infection in vivo (15). Thus, both studies supported the hypothesis that, in addition to functioning as a MAC inhibitor, CD59 works as a suppressor of T cell immunity via a novel and complement-independent mechanism. Finally, our results and those of Longhi et al. (15) are consistent with the substantial literature documenting a role of CD59 in T cell activation and signal transduction, either in the capacity as a GPI-anchored protein in lipid rafts of the T cell plasma membrane (43, 44) or as a cellular ligand for the T cell coreceptor CD2 (43, 45, 46).

In summary, we have revealed in this study a prominent role for CD59a in regulating autoimmunity in MRL/lpr mice. Deletion of CD59a exacerbated a number of features of the murine SLE. The effect of CD59a was independent of complement and was conferred by its expression on both BM-derived cells and peripheral tissues. Although the precise mechanisms of this novel function of CD59a remain to be elucidated, our findings have raised the possibility of a similar role of CD59 in human SLE and suggested new avenues of investigation in the pathogenesis and therapy of human autoimmune diseases.

Disclosures

The authors have no financial conflicts of interest.

References