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Complement C4 Is Protective for Lupus Disease Independent of C3¹

Shirit Einav, Olga O. Pozdnyakova, Minghe Ma, and Michael C. Carroll²

The role of complement C3 in mediating systemic lupus erythematosus (SLE) was examined using a double-knockout C3^{null}C4^{null} Fas (CD95)-deficient mouse model. Results from this study reveal significant lymphadenopathy, splenomegaly, elevated titers of anti-nuclear Abs and anti-dsDNA Abs, an increased number of anti-dsDNA-producing cells in ELISPOT assay, as well as severe glomerulonephritis in the double-deficient mice. Based on these clinical, serological, and histological parameters, we find that autoimmune disease in the double-knockout group is similar in severity to that in C4^{null} *lpr* mice, but not to that in C3^{null} *lpr* mice. The development of severe SLE in the absence of both classical and alternative complement pathways suggests that it is the absence of C4, and not the presence of C3, that is critical in SLE pathogenesis. Thus, complement C4 provides an important protective role against the development of SLE. *The Journal of Immunology*, 2002, 168: 1036–1941.

Systemic lupus erythematosus (SLE)³ is a relatively common autoimmune disorder, occurring in 20–130 of every 100,000 people in the United States (1). The association between the complement system and SLE is contradictory. While complement is a mediator of inflammation, complement deficiency predisposes to the development of SLE. Inherited complement C1q or C4 deficiencies, whether partial or complete, confer a high risk to develop SLE (2–5), whereas C3 deficiency is only rarely associated with SLE-like illness (2, 6, 7).

Two models have been proposed to explain the role of complement in lupus. The first is based on the hypothesis that complement plays a substantial role in the clearance of immune complexes and/or apoptotic debris (8, 9), which is thought to be impaired in lupus. Apoptotic bodies are a potential major source of lupus self-Ags, and failure to remove them could lead to inappropriate production of pathogenic autoantibodies (10). Support for a role for early complement in clearance of apoptotic debris comes from the finding that C1q binds directly to apoptotic blebs (11) and that mice deficient in C1q or C4 have defects in the clearance of injected apoptotic thymocytes (12). Moreover, mice deficient in C1q (9) or C4 (13) spontaneously develop autoantibodies against nuclear Ags. The presence of increased apoptotic bodies in the affected glomeruli of C1q-deficient mice (9) supports this model.

A second, nonexclusive model proposes that the innate immune system, including complement, is protective against lupus by enhancing negative selection of self-reactive B cells. According to this hypothesis, innate proteins enhance the localization of lupus Ags such as dsDNA and nuclear proteins within the primary lym-

phoid compartment. Efficient presentation of self-Ags results in elimination or editing of potential self-reactive B cells (14). Thus, deficiency in innate proteins such as serum amyloid protein (15), DNase I (16), natural IgM (17, 18), C1q (19), or C4 (13) could lead to an escape from negative selection by self-reactive B cells and their potential activation in the periphery in the presence of cognate T cell help and lupus Ag.

Support for this latter model comes from a study with C4^{null}, CR2^{null}, and C3^{null} mice crossed with mice bearing transgenes specific for both anti-hen lysozyme and a soluble form of lysozyme Ag (20). This study found that C4 and CR2, but not C3, are critical in maintaining tolerance to the self-Ag (21). Further support comes from studies with a complement-deficient *lpr* model. Mice homozygous for the *lpr* (lymphoproliferation) mutation are Fas (CD95) deficient. Deficiency is associated with a lupus-like disease, the severity of which is dependent on background genes (22, 23). C57BL/6.*lpr* and C57BL/6 × 129 *lpr* mice have a mild form of the disease, with only minimal renal involvement (24). Significantly, deficiency for C4 and CR2, but not C3, in combination with *lpr* on the C57BL/6 × 129 background results in increased severity of lupus-like disease, including renal involvement (21).

The results in the *lpr* model raise the question: does C3 deficiency protect against lupus? C3 may be required for Ag clearance or tolerance, but the effect is negated by its alternative role as a mediator of inflammation or enhancer of humoral immunity (25). Accordingly, C3-deficient mice might be lupus susceptible, as are C1q- and C4-deficient mice, but fail to develop the disease because of an impairment in inflammation or their ability to mount an immune response. Interestingly, kidney disease is not C3 dependent in the MRL/*lpr* murine lupus strain (26) or the (NZB/NZW)_{F1} strain, where disease appears to be mediated by Ab and the FcγR (27). C3 also does not appear to be required for spontaneous disease in C1q-deficient mice (19). By contrast, an intact alternative pathway is required for full pathogenesis in MRL/*lpr* mice (28). In this study MRL/*lpr* mice deficient in factor B developed a mild disease phenotype. Susceptibility to lupus disease is multigenic; therefore, the production of autoantibodies and the mechanism of pathology are likely to vary among different strains of mice.

To test the hypothesis that C3 deficiency is protective against the development of lupus, C3^{null} *lpr* mice were crossed with C4^{null} *lpr* mice. The resulting double-knockout group was found to have

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³ Abbreviations used in this paper: SLE, systemic lupus erythematosus; AFC, Ab-forming cell; ANA, anti-nuclear Ab; AP, alkaline phosphatase; BM, bone marrow; C⁺, complement-sufficient; LN, lymph node.

SLE disease similar in severity to that reported in the C4^{null} *lpr* group. These findings demonstrate that C3 is not essential to the development of a lupus-like phenotype in *lpr* mice; therefore, the absence of increased severity of disease is not due to its role in inflammation or the humoral immune response.

Materials and Methods

Mice

C3^{null} and C4^{null} mice on a mixed C57BL/6 × 129/sv background were bred with C57BL/6*lpr/lpr* mice purchased from The Jackson Laboratory (Bar Harbor, ME). Double-knockout C3^{null}C4^{null} *lpr* mice were then obtained by breeding C3^{null} *lpr* with C4^{null} *lpr* mice. Genotyping was performed by PCR (29). Complement-sufficient *lpr* mice were used as controls. All experiments were performed on age- and sex-matched mice maintained under specific pathogen-free conditions.

Immunofluorescence for detection of autoantibodies

Anti-nuclear Abs (ANA) and anti-dsDNA Abs were measured in the serum by indirect immunofluorescence using HEP-2-coated slides and *Crithidia luciliae* substrate slides (The Binding Site, Birmingham, U.K.), respectively. Slides were first incubated for 20 min with serial dilutions of mouse serum in PBS. After PBS washing, FITC-labeled goat anti-mouse IgG (whole molecule; Sigma-Aldrich, Poole, U.K.) was added for 20 min. All stages were performed in a dark, humid chamber at room temperature. Slides were then washed, mounted with Toluene acrylic resin mounting medium (Stephens Scientific, Riverdale, NJ), and viewed by fluorescent microscopy. Titers are reported as inverse values of the last positive dilutions, compared with the 1/40 dilution of wild-type controls. Mean values were calculated for each group.

ELISA for anti-dsDNA Abs

Anti-dsDNA Abs were detected in the serum by modified ELISA, performed as previously described (23, 24, 26, 28, 30). Subsequently, 96-well polystyrene microtiter plates (Immunol1; Dynex Technologies, Chantilly, VA) were serially incubated overnight at 4°C with avidin (Sigma-Aldrich), and photobiotinylated circular or linear plasmid DNA were prepared according to the manufacturer's protocol (Sigma-Aldrich). Wells were washed three times with PBS and 0.02% Tween (PBST) between each step. After blocking with 1% BSA/PBST for 1 h at 37°C, plates were incubated for 2 h at 37°C with serial dilutions of mouse serum in 1% BSA/PBST. Alkaline phosphatase (AP)-conjugated goat anti-mouse whole molecule IgG Abs (Sigma-Aldrich) diluted to 1/500 in 1% BSA/PBST were incubated for 1 h at 37°C. AP substrate (Sigma-Aldrich) was added, and OD was read 30 min later. The anti-dsDNA IgG concentration was approximated using a standard curve obtained from serial dilutions of a mouse serum with known IgG concentration and from standard IgG product (Southern Biotechnology Associates, Birmingham, AL). Mean values were calculated for each group. As a negative control serum samples were applied to plates uncoated with the Ag or with anti-IgG.

ELISPOT assay for anti-dsDNA AFCs

An ELISPOT assay for quantitation of anti-dsDNA Ab-forming cells (AFCs) was performed as previously described (31). Cell suspensions were prepared from fresh spleens, lymph nodes (LN), and bone marrow (BM) on a Ficoll-Paque gradient (Amersham Pharmacia Biotech, Uppsala, Sweden) in DMEM (Life Technologies, Grand Island, NY). Serial dilutions of these suspensions, starting with 10⁶ cells/well, were incubated overnight at 37°C in a 5% CO₂ air incubator on 48-well polystyrene plates (Costar, Cambridge, MA) previously coated with avidin (Sigma-Aldrich) and photobiotinylated plasmid DNA and blocked with 1% BSA/PBST. The cells were washed away, and plates were overlaid with AP-conjugated goat anti-mouse IgG Abs (Sigma-Aldrich) diluted to 1/500 in 1% BSA/PBST for 1 h at 37°C. The AP substrate was maintained at 60°C and consisted of 2.3 mM 5-bromo-3-chloroindolyl phosphate solution (Sigma-Aldrich) in 2-amino-2-methyl-1-propanol buffer (Sigma-Aldrich) mixed with 0.6% agarose (Sigma-Aldrich). After overnight incubation at 4°C, blue spots were routinely read by light microscopy under ×100 magnification. Each spot represents Abs produced by an individual B cell that bound to the plate. Controls included cells incubated on plates without Ag or anti-IgG and DMEM alone without cells. Results represent either the number of anti-dsDNA IgG-secreting cells per 10⁶ cells applied or per total number of IgG-secreting cells (determined in the various organs by using anti-IgG-coated plates). The number of splenic anti-dsDNA IgG-secreting cells was also calculated per total number of splenic lymphocytes. Mean values were calculated for each group.

Kidney staining

Kidneys were quick-frozen in OCT for immunofluorescence staining. Cryosections, 5 mm thick, were stored 24 h or longer at −80°C and then fixed with *m*-periodate-lysine paraformaldehyde fixative (32) for 30 min. After blocking with 5% milk (Carnation instant milk; Nestle, Solon, OH) in PBST for 30 min, slides were incubated for 1 h with FITC-labeled goat anti-mouse whole molecule IgG (Sigma-Aldrich) or anti-mouse C3 or C4 diluted to 1/200 in 1% BSA/PBS. All stages were performed in a humid dark chamber at room temperature. Slides were washed three times with 1% BSA/PBST between each step. Slides were mounted with Toluene acrylic resin mounting medium (Stephens Scientific) and then viewed by fluorescence microscopy. The number of stained glomeruli was counted and divided by the total number of glomeruli seen in 10 high power fields. Mean values for each group were calculated.

Alternatively, kidneys were fixed in 10% buffered formaldehyde (Fisher Scientific, Fair Lawn, NJ) and stained with H&E or periodic acid-Schiff. These sections were classified into four categories based on the degree of glomerular enlargement, hypercellularity, mesangial thickening, hyalin deposition, presence of crescents, and fibrosis using the following scoring system: 0 for <10% glomeruli affected, 1 for 10–30% glomeruli affected, 2 for 30–75% glomeruli affected, 3 for 75–95% glomeruli affected, and 4 for >95% glomeruli affected.

Statistical methods

The significance of mean values was determined by Student's *t* test. Values of *p* > 5% were considered insignificant. Linear correlation was analyzed by a correlation test.

Results

Mass of cervical LNs and spleen

Splenomegaly and lymphadenopathy are known manifestations of Fas deficiency and are considered clinical markers for the severity of SLE (22). To estimate the severity of lupus disease in C3^{null}C4^{null} *lpr* mice, the mass of cervical LNs and spleen was measured and compared with that in the C4^{null} and C3^{null} *lpr* groups. Females in three age groups, ranging from 10 to 17 wk, were evaluated.

As reported previously, the mass of cervical LNs was significantly greater in C4^{null} *lpr* mice than in C3^{null} *lpr* and complement-sufficient (C⁺) *lpr* controls at 10 and 13 wk (Fig. 1*a*) (21). At 17 wk the LN mass was also elevated in C3^{null} mice, but the relative increase was not significant, in contrast to C4^{null} *lpr* mice. Interestingly, combined deficiency in C3 and C4 did not protect against increased lymphadenopathy. A significant increase in the mass of cervical LNs was observed in the double-deficient mice at both 10 and 13 wk (Fig. 1*a*). Thus, the absence of lymphadenopathy of the C3^{null} *lpr* mice was not explained by a requirement for C3. The effects of C4 deficiency were less pronounced on splenomegaly. However, at 17 wk all three deficient groups developed enlarged spleens relative to C⁺ *lpr* mice (Fig. 1*b*).

Lupus autoantibodies

A hallmark of lupus is increased ANAs. Previous studies indicated a significant increase in ANA titer in C4^{null} *lpr* mice relative to C3^{null} and C⁺ *lpr* controls. An explanation for the decreased ANA in C3^{null} *lpr* mice is that complement C3 is critical for an effective humoral response (25). To test this hypothesis, ANA titers were assayed for each of the four groups of mice by indirect immunofluorescence on HEP-2 slides. As predicted, Ab titers in C4^{null} *lpr*, but not C3^{null} *lpr* mice, were significantly elevated related to those in C⁺ controls at each of the three time points. Comparison of the C3^{null}C4^{null} *lpr* mice with the single-deficient strains revealed a similarly significant increase in ANAs at 10 and 17 wk. Titers were elevated in double-deficient mice at 13 wk, but the increase was not statistically significant. In general, the mean ANA was slightly greater in C4^{null} *lpr* mice than in C3^{null}C4^{null} *lpr* in each age group, but the increases were not statistically significant (results not shown).

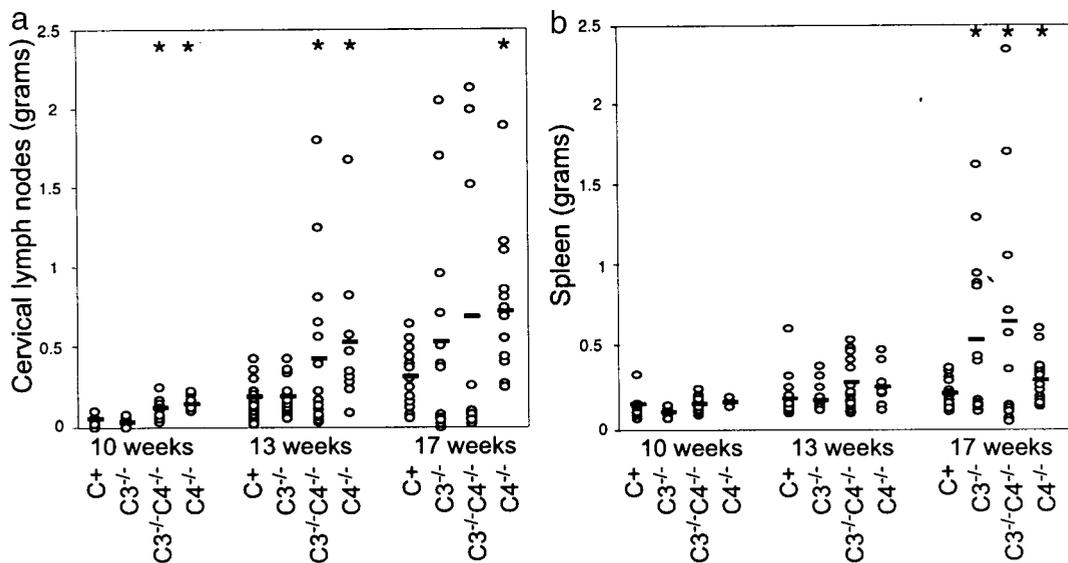


FIGURE 1. Deficiency in C4 alone or in C4 and C3 results in increased lymphadenopathy (a) and splenomegaly (b) in *lpr* mice. Cervical LNs and spleen from mice, sacrificed at the ages of 10, 13, or 17 wk, were weighed. Each age group from each strain included 5–10 mice (females). Circles represent individual mice; bars represent mean values. *, Statistical significance ($p < 0.05$).

Serum concentrations of anti-dsDNA Abs were elevated in C4^{null} *lpr* mice as predicted based on earlier results (21). Likewise, the mean anti-dsDNA titer was elevated in the double-deficient mice but reached statistical significance only in the 17-wk-old mice. In 13- and 17-wk-old mice there was a slight increase in the mean anti-dsDNA titers of C3^{null}C4^{null} *lpr* vs C4^{null} *lpr*. This finding is in contrast to that for ANAs (Fig. 2b), although the difference was not significant. To confirm the ELISA results, anti-dsDNA Abs were measured using *Crithidia luciliae* slides. An 0.87 correlation was found between the two assays (data not shown). Ten percent of the sera tested were positive for anti-dsDNA Abs measured by ELISA but not by indirect immunofluorescence. Similarly, ELISA results positively correlated with ANA titers (correlation coefficient of 0.73).

ANA patterns in the C4^{null} and C3^{null}C4^{null} *lpr* groups were highly variable (including nucleolar, nuclear matrix, cytoplasmic speckles, etc.), as opposed to the homogeneous and fine speckles predominantly seen in C⁺ *lpr* and C3^{null} *lpr* groups (Fig. 3). Several sera from the C4-deficient groups demonstrated mixed ANA patterns. In these sera different fluorescence patterns were produced with different dilutions.

In general, deficiency in complement C3 did not appear to impair the autoantibody response to nuclear or dsDNA self-Ags.

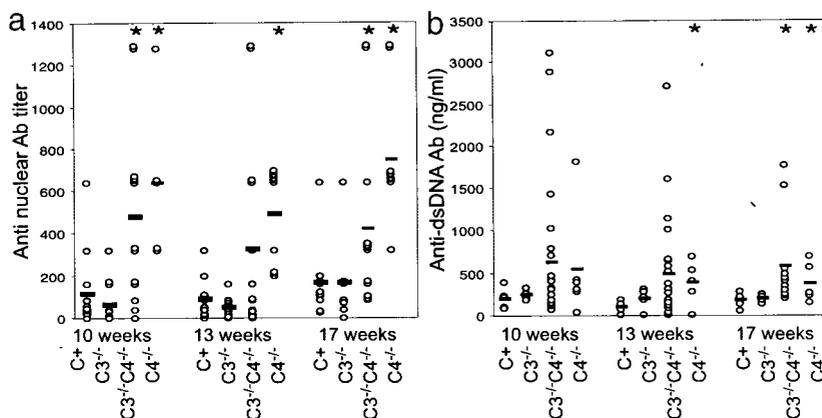
Therefore, the lack of increased autoantibodies in C3^{null} *lpr* mice is not explained by an impairment in humoral immunity.

Anti-dsDNA AFCs

To determine the frequency of dsDNA-AFCs, cell suspensions were prepared from spleens, LNs, and BM of each group of mice and analyzed by ELISPOT assay on dsDNA-coated plates. Consistent with increased ANA and dsDNA titers, the mean frequency of dsDNA ASCs was elevated in all three lymphoid tissues of C4^{null} *lpr* mice relative to those in C3^{null} *lpr* and C⁺ *lpr* (Fig. 4). However, the increase was statistically significant only in spleen and BM. As predicted from the autoantibody titers, *lpr* mice bearing C3 and C4 deficiency have a significant increase in the frequency of AFCs in all three lymphoid compartments relative to C⁺ *lpr* mice. In LNs and BM, an increase in mean AFC was observed in the C3^{null}C4^{null} *lpr* animals relative to C4^{null} *lpr* mice, but the difference was not significant. A minimal number of anti-dsDNA-AFCs was observed in wild-type controls (data not shown), while no spots developed in the absence of Ag, cells, or anti-IgG Abs.

To determine whether the relative increase in AFCs was dsDNA specific or represented a general increase in total IgG-producing cells, results were expressed relative to the total number of IgG-secreting cells. Splenic dsDNA-AFCs constituted a significantly

FIGURE 2. Deficiency in C4 or C4 combined with C3 results in increased ANA (a) and anti-dsDNA (b) levels in *lpr* mice. Mice from each strain were bled at 10, 13, or 17 wk age (10 females in each age group in each strain). ANA titers were measured in the serum by indirect immunofluorescence on Hep-2-coated slides. Anti-dsDNA titers were measured by ELISA and converted to concentrations using a standard curve. Circles indicate individual mice; bars represent mean values. *, Statistical significance ($p < 0.05$).



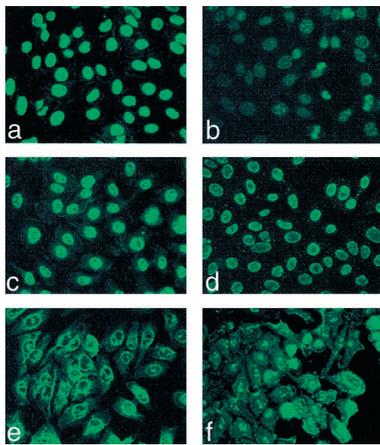


FIGURE 3. Nuclear homogeneous (a) and fine speckles (b) patterns predominated in the C^+ *lpr* and $C3^{\text{null}}$ *lpr* mice groups, whereas several ANA patterns and occasionally mixed patterns were seen in the $C4^{\text{null}}$ and $C3^{\text{null}}C4^{\text{null}}$ *lpr* groups. HEP-2 cells were treated with dilutions of mouse serum as described in Fig. 2. Other patterns observed were nuclear matrix (c), homogenous nuclear with cytoplasmic speckles (d), nucleolar with nuclear rim (e), and nucleolar with cytoplasmic speckles (f). Results are representative of 10 different fields of view and examination of serum samples taken from at least three mice from each group. Magnification, $\times 100$.

higher proportion of IgG-secreting cells in $C4^{\text{null}}$ and $C3^{\text{null}}C4^{\text{null}}$, but not $C3^{\text{null}}$ *lpr*, mice compared with C^+ *lpr* controls. Mean values ranged between 8 and 13.6% in the $C4$ -deficient strains, while the values for $C3^{\text{null}}$ and C^+ *lpr* controls were 2.5 and 2.9%, respectively. However, $C3^{\text{null}}$, $C4^{\text{null}}$, and $C3^{\text{null}}C4^{\text{null}}$ *lpr* strains exhibited a similar proportion of B cells secreting anti-dsDNA in the BM and LNs compared with that of C^+ *lpr* controls. In all groups the highest proportion of B cells secreting anti-dsDNA was

found in the spleen, followed by the LNs and finally BM; proportions tended to increase with age (data not shown). The results suggest that the increase in splenic AFCs is DNA specific and not due to an overall B cell hyperactivity.

Deposition of immune complexes in kidneys

Glomerulonephritis is an important diagnostic and prognostic factor in lupus. Consistent with a previous report by Prodeus et al. (21), immunofluorescent staining of renal cryosections revealed increased IgG deposition in $C4^{\text{null}}$ *lpr* mice, but not $C3^{\text{null}}$ *lpr* mice, relative to C^+ *lpr* controls ($p < 0.001$). IgG deposition in the $C3^{\text{null}}C4^{\text{null}}$ *lpr* group was similar to that in the $C4^{\text{null}}$ *lpr* group, i.e., 72 and 65%, respectively (Table I). Affected glomeruli among C^+ *lpr* controls averaged 38%, whereas the incidence among the $C3^{\text{null}}$ *lpr* group was lower (32%). As expected, no staining was observed in the $C3^{\text{null}}C4^{\text{null}}$ *lpr* group, and C3 and C4 deposition was absent in $C3^{\text{null}}$ and $C4^{\text{null}}$ *lpr* mice, respectively. Paraffin-embedded renal sections stained with H&E or periodic acid-Schiff were also evaluated for glomerular abnormalities (Fig. 5). Examination of sections revealed statistically significant ($p < 0.02$) higher mean pathology scores among $C4^{\text{null}}$ *lpr* mice compared with C^+ *lpr* controls, while only a minimal increase was observed in the $C3^{\text{null}}$ *lpr* group. Once again, results for the double-knockout *lpr* group and $C4^{\text{null}}$ *lpr* group were similar.

Discussion

Deficiency in C4 accelerates the autoreactive phenotype of *lpr* mice on the mixed B \times 129 background, resulting in increased lymphadenopathy, splenomegaly, anti-nuclear and anti-dsDNA Ab levels, and glomerular injury (21). This acceleration is also evident in the $C3^{\text{null}}C4^{\text{null}}$ *lpr* mice but not in the $C3^{\text{null}}$ *lpr* mice. These findings not only implicate a dominant role for C4 in protection against autoimmune disease but also reveal that C3 is not required

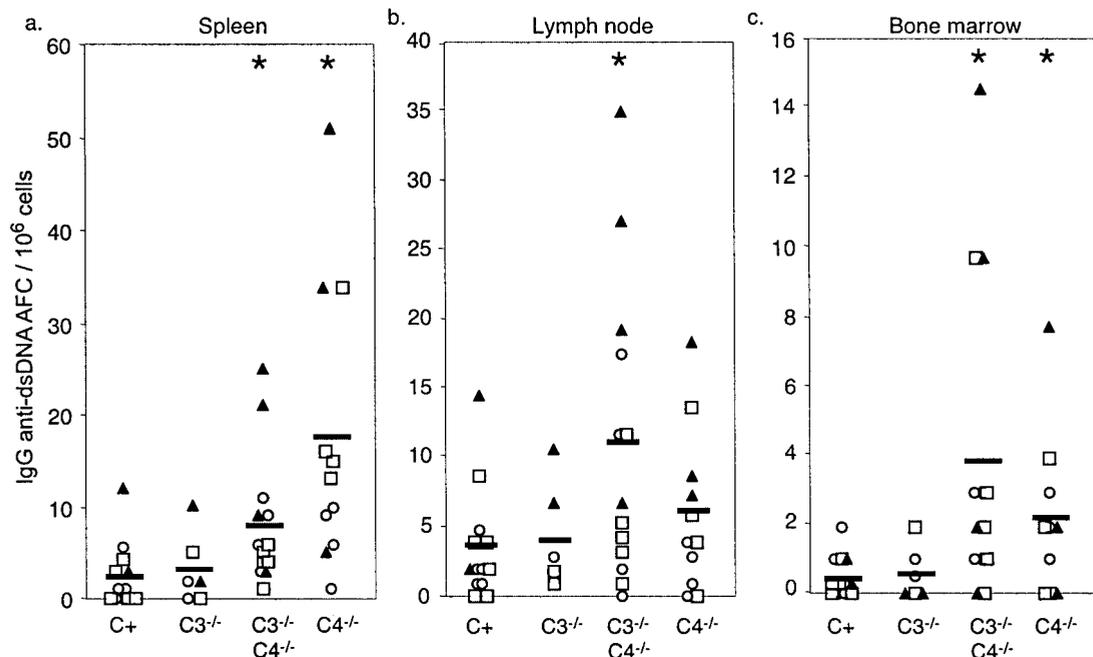


FIGURE 4. $C4^{\text{null}}$ and $C3^{\text{null}}C4^{\text{null}}$ *lpr* mice exhibit a significant increase in the number of anti-dsDNA AFCs compared with $C3^{\text{null}}$ and C^+ *lpr* controls in spleen (a), LNs (b), and BM (c). Anti-dsDNA AFCs were counted by ELISPOT assay performed on fresh spleens, LNs, and BM cell suspensions prepared from four groups of *lpr* female mice at 10, 13, and 17 wk of age ($n = 2-6$ mice per age group). The number of spots per 10^6 lymphocytes applied is shown. Symbols represent individual mice at different age groups: ○, 10 wk; □, 13 wk; ▲, 17 wk. Bars indicate mean values. *, Statistical significance. The results represent two experiments.

Table I. IgG deposition in kidney sections^a

Weeks	C ⁺ <i>lpr</i>	C3 ^{null} <i>lpr</i>	C4 ^{null} <i>lpr</i>	C3 ^{null} C4 ^{null} <i>lpr</i>
10	36.44	32.16	65.46	59.2
13	31.94	33.33	69.16	66.53
17	44.33	30.99	80.00	67.88
Total mean	37.57	32.16	71.52	64.53

^a Immunofluorescent staining of renal cryosections for IgG revealed statistically significant ($p < 0.001$) increased IgG deposition in C4^{null}, C3^{null}C4^{null}, but not C3^{null}, *lpr* mice, when compared with C⁺ *lpr* controls. The average percentage of glomeruli demonstrating IgG deposition in each strain in different age groups is shown. $n = 5$ for each age group for each strain.

for progression of SLE and the development of glomerulonephritis in *lpr* mice on a mixed B6 × 129 background.

The double-deficient C3^{null}C4^{null} *lpr* mice exhibited increased immune complex deposition and glomerular abnormalities similar to those found in C1q-deficient mice crossed with mice deficient in factor B and C2 (19). In light of the multigenic nature of lupus and the likely variation in autoantibodies and mechanism of pathology among mice of different backgrounds, it is important to establish the role of complement in the various disease models. Thus, the protective effects of complement supersedes its role as a mediator of inflammation. Significantly, the role of complement as an enhancer of humoral immunity is also circumvented in this model, as the double-deficient *lpr* mice develop high titers of IgG autoantibodies (33). One explanation for this phenomenon is that the abundance of self-Ag overrides the general requirement for complement localization of Ag and coreceptor signaling of B cells (34).

Splenic ELISPOT results support the hypothesis that the absence of C4 leads to an increase in the number of self-reactive B cells (Fig. 4). Activation of self-reactive B cells was made evident by the increased absolute numbers of splenic anti-dsDNA-AFC.

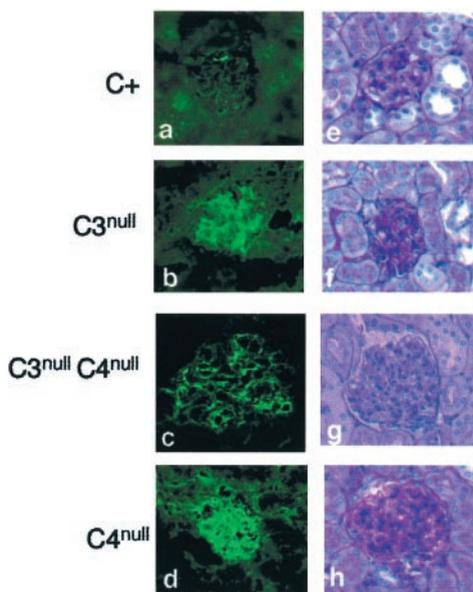


FIGURE 5. Kidney staining. Deficiency in C4 or C4 combined with C3 results in increased glomerular damage due to immune complex deposition. *a–d*, Representative glomeruli ($n = 5$) of renal cryosections treated with goat anti-mouse IgG, followed by fluorescence-labeled secondary Ab. This is a summary of the results presented in Table I. *e–h*, Representative glomeruli of paraffin-embedded renal sections stained with periodic acid-Schiff. Results identify hypercellularity, glomerular enlargement, mesangial thickening, hyalin deposition, and fibrosis in *g* and *h* and relatively normal-appearing glomeruli in *e* and *f*.

The range of the average values is similar to that reported in (NZB × NZW)F₁ mice, in which clinical parameters of nephritis correlated better with this assay than with serum autoantibodies (35). The relative proportion of B cells producing anti-DNA Abs in the spleens of MRL/*lpr/lpr* mice was reported previously (36). However, the differential frequency of these cells in the various lymphoid compartments was not discussed. MRL/*lpr/lpr* mice have a mean value range of 0.76–3% (ss+ds)DNA-AFC per total IgG-secreting cells (36).

Peripheral blood B cells from lupus patients exhibited values as high as 5%, with mean values of 0.6 and 1% in CD5⁺ and CD5⁻ B cell subsets, respectively, (37). The increased frequency of dsDNA-AFC in the spleens of complement-deficient *lpr* mice, but not C⁺ controls, is consistent with findings in human SLE. ELISPOT analysis of peripheral blood cells of lupus patients revealed an increased number of DNA-AFC relative to total IgG, in contrast to that observed with environmental Ags (38). This suggests that B cell activation is specific for lupus Ags. By contrast, BM and LNs from the complement-deficient mice exhibited a similar proportion of dsDNA-AFCs as C⁺ controls despite having a higher absolute number of anti-DNA-secreting cells per 10⁶ cells.

The heterogeneous ANA pattern suggests the presence of auto-reactive B cells directed against a large array of self-Ags in the absence of C4. This is evidenced by the larger variety of ANA-staining patterns in C4-deficient *lpr* strains compared with complement C⁺ controls (Fig. 3). The mixed ANA pattern demonstrated in several sera of the complement-deficient groups suggests the presence of several autoantibodies in the same mice.

In summary, complement C4 is protective against SLE in B6 × 129 *lpr* mice. By contrast, despite its role in the immune clearance function, C3, the central component of complement, is not protective. Moreover, the severity of disease in *lpr* mice with a deficiency in both C4 and C3 is similar to that in C4 *lpr* mice, demonstrating that the lupus-like phenotype is not dependent on C3.

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