Decay-accelerating factor modulates induction of T cell immunity

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Decay-accelerating factor (Daf) dissociates C3/C5 convertases that assemble on host cells and thereby prevents complement activation on their surfaces. We demonstrate that during primary T cell activation, the absence of Daf on antigen-presenting cells (APCs) and on T cells enhances T cell proliferation and augments the induced frequency of effector cells. The effect is factor D- and, at least in part, C5-dependent, indicating that local alternative pathway activation is essential. We show that cognate T cell–APC interactions are accompanied by rapid production of alternative pathway components and down-regulation of Daf expression. The findings argue that local alternative pathway activation and surface Daf protein function respectively as a costimulator and a negative modulator of T cell immunity and explain previously reported observations linking complement to T cell function. The results could have broad therapeutic implications for disorders in which T cell immunity is important.

Complement directly destroys invading pathogens and is a source of anaphylatoxins that attract phagocytic cells to sites of insult (1). In adaptive immune responses, it is the effector system for antibody-mediated immunity. Previous studies have indicated that complement influences alloimmune, autoimmune, antiviral, and antitumor T cell responses (2–5), but these observations remain largely unexplained. Because protective antiviral and antitumor T cell reactivity as well as T cell memory are highly dependent on the size of the induced effector T cell repertoire (6–8), clarifying how complement shapes the effector T cell repertoire has broad biological and clinical implications.

Decay-accelerating factor (Daf) is a ubiquitously expressed intrinsic complement-regulatory protein whose function is to dissociate C3/C5 convertases on host-cell surfaces (9), thereby limiting local C3a/C5a anaphylatoxin production and C3b/C5b-initiated progression of the cascade. Daf also has been identified as a ligand for CD97, a leukocyte- and endothelial cell-associated member of the epidermal growth factor family of proteins, which has been identified as a Daf adhesin for attracting leukocytes (10, 11). Although it is known that Daf, a glycoprophatidylinositol-anchored protein (12, 13), is expressed in lipid rafts on T lymphocytes and can be found in the general proximity of the TCR complex (14, 15), no direct or indirect role for Daf in controlling T cell immunity has previously been described. Here we report the unanticipated findings that Daf modulates T cell immunity by controlling T cell– and APC-induced alternative pathway C3 activation during cognate interactions.

RESULTS AND DISCUSSION

To address whether Daf influences cellular immune responses, we studied splenocytes obtained from mice made genetically deficient in the Daf1 gene (Daf1−/−, H-2b) and from Daf1+/+ littermates. Initial studies, using mixed lymphocyte cultures in which H-2b Daf1−/− or control Daf1+/+ spleen cells were stimulated with allogeneic H-2b spleen cells in vitro, revealed that Daf1−/− cells responded more vigorously than did control Daf1+/+ cells (Fig. 1 A). Reconstitution of Daf1−/− spleen cells with lipid-tailed mouse Daf protein attenuated the increased responsiveness (Fig. 1, A and B), verifying that the effects were specific to Daf deficiency. Substantiating this interpretation, the addition of anti-Daf mAb 2C6 specifically increased the number of induced alloreactive, WT effector T cells (Fig. 1 C).

The online version of this article contains supplemental material.
To differentiate antigen-induced versus bystander effects of Daf inhibition on T cell activation, we performed studies using TCR transgenic T cells. The frequency of peptide-activated TCR transgenic Mar T cells (C57BL/6, H-2<sup>b</sup>, RAG2<sup>-/-</sup>, specific for male antigen HY<sub>Dby</sub>) was similarly increased in the presence of anti-Daf mAb but not of control mAb (Fig. 1 C).

We next evaluated in vivo T cell responses induced to the male antigen, HY. H-2<sup>b</sup> female mice reject H-2<sup>b</sup> male skin grafts using T cells specific for class II MHC–restricted HY<sub>Dby</sub> and class I MHC–restricted HY<sub>Uty</sub> (16). As shown in Fig. 2 A, transplantation of Daf<sup>1+/+</sup> females with Daf<sup>1+/-</sup> male skin grafts resulted in a 1.5- and threefold increased frequency of anti-HY CD4 and CD8 T cells, respectively, when compared with control Daf<sup>1+/-</sup> females engrafted with Daf<sup>1/-</sup> male skin. For the CD4 response, the absence of Daf on either the donor or the recipient similarly enhanced T cell immunity; for the CD8 response, a greater effect was noted when the recipient was Daf<sup>1/-</sup> (Fig. 2 A). The increased frequency of anti-HY T cells was associated with a 2-d acceleration of graft destruction (median survival, 14 d for Daf<sup>1+/-</sup> to Daf<sup>1+-/+</sup> vs. 12 d for Daf<sup>1/-</sup> to Daf<sup>1+/-</sup>, Daf<sup>1+/-</sup> to Daf<sup>1+/-</sup>, or Daf<sup>1+/-</sup> to Daf<sup>1+/-</sup>; n = 4–8/group; P < 0.05). Similarly, alloreactive T cells in recipient C3H mice (H-2<sup>k</sup>) primed at 10-fold higher frequencies to allogeneic Daf<sup>1+/-</sup> (8500/10<sup>6</sup> anti-H-2<sup>b</sup> IFN<sub>γ</sub>-producers) versus Daf<sup>1+/+</sup> (520/10<sup>6</sup> anti-H-2<sup>b</sup> IFN<sub>γ</sub> producers; n = 3/group; P < 0.05) heart grafts.

We next asked how APC-expressed (as opposed to T cell-expressed) Daf affects T cell reactivity. H-2<sup>b</sup> Daf<sup>1+/-</sup> splenic stimulators primed approximately sixfold higher frequencies of alloreactive IFNγ-secreting C3H (H-2<sup>k</sup>) effector
from ninth-generation backcross Daf1−/− (101 ± 18/10^6 C3H T cells) and Daf1+/+ littermates (45 ± 11/10^6 C3H T cells; P < 0.05). Responder C3H T cells also proliferated more vigorously both in vitro and in vivo (Fig. 3, B and C) when stimulated with allogeneic Daf1−/− APCs versus Daf1+/+ APCs. Female Mar T cells responded up to fivefold more vigorously, both in vitro (Fig. 3 D) and in vivo (Fig. 3 E), when stimulated with male H-2k stimulator cells from Daf1−/− mice than from Daf1+/+ controls, confirming an antigen-specific effect. Mar cells also responded at higher frequency in vitro to splenic APCs from ninth-generation backcross by 5,6-carboxy-2,7-dechlorofluorescein (CFSE) proliferation (3.01% vs. 0.49% of Mar cells divided >2 times in Daf1−/− vs. Daf1+/+, respectively) and ELISPOT (127 ± 12 IFNγ producers/10^5 cells with Daf1−/− APCs vs. 46 ± 5 with Daf1+/+ APCs. P < 0.05).

We next asked if the absence of Daf on T cells affects the induced T cell immune response. As assessed by IFNγ ELISPOT (Fig. 4 A) or CFSE dilution (not depicted), Daf1−/− T cells responded more vigorously than Daf1+/+ T cells to Daf1+/+ allogeneic stimulator cells. Moreover, Thy1.2+ Daf1−/− T cells responded to in vivo immunization more vigorously than Thy1.2+ Daf1+/+ T cells when the T cells were transferred into congenic Thy1.1+ Daf1+/+ recipients (the Thy1.1 and Thy1.2 antigens allowed differentiation of the transferred T cells from the endogenous T cells; Fig. 4 B). The effect was similar but smaller in magnitude than when Daf protein was deficient on the APCs (Fig. 3).

To determine if the augmenting effect of Daf deficiency relates to work published in the 1980s that Daf cross-linking transmits a proliferative signal (17), we tested in vitro female responses to HYDby. 5 d of in vitro culture with HYDby peptide induced a significantly higher frequency of effector IFNγ producers from Daf1−/− splenocytes compared with Daf1+/+ spleen cells (52 ± 9 vs. 13.8 ± 4/200,000 spleen cells; mean of n = 4/group; P < 0.05). Frequencies of HYDby-reactive IFNγ and IL-2 producers were identical (Daf1−/− APCs vs. 46 ± 5 with Daf1+/+ APCs). P < 0.05).

Figure 2. Deficiency of Daf protein augments cellular immunity in vivo. (A) IFNγ ELISPOT assays were performed at rejection of male to female skin grafts (+/+; Daf1+/−; −/−, Daf1−/−) to assess reactivity to male peptides HYDby (left) and HYUty (right). Each symbol represents an individual animal (mean of triplicate wells, SD < 15%), –, means for all animals per group (n = 4–8); * P < 0.05 versus Daf1+/+ to Daf1+/+. No response (<10 IFNγ producers/500,000 cells) was detected in any animal to control antigens OVA122-133 and β-gal146-153, and no responses were detected in naive mice (not depicted). (B) Spleen cell responses by IFNγ ELISPOT 12 d (top) or 30 d (bottom) after immunization of Daf1−/− or Daf1+/+ mice with HYDby peptide plus CFA. No response was detected to control antigens (not depicted). Means plus SD for three to five animals/group are shown. The results are fully representative of two to four independent experiments. * P < 0.05.

T cells than control Daf1+/+ H-2k spleen cells (Fig. 3 A). This effect was abrogated by incorporation of recombinant lipid-tailed mouse Daf onto the surface of the Daf1−/− spleen cells (Fig. 3 A). Although these data were obtained using APCs from mice backcrossed four generations to C57BL/6, similar results were obtained using splenic APCs
Figure 3. Daf1−/− APCs augment T cell immunity in vitro and in vivo via alternative complement activation. (A) H-2k T cells mixed with allogeneic H-2b splenic stimulators with or without rDaf were tested in IFNγ ELISPOT assays (means plus SD; n = 3 replicates/group). (B) Proliferation of CFSE-labeled WT H-2k T cells versus allogeneic Daf1−/− or Daf1+/+ macrophages on d 5. The precursor frequencies of responding T cells were 1.01% (4.1% underwent more than three divisions) against Daf1−/− cells versus 0.07% against Daf1+/+ cells (1.1% underwent more than three divisions). (C) Proliferation of splenic CFSE-labeled H-2k T cells on day 5 after injection into allogeneic hosts. The mean numbers of transferred cells that underwent more than three cell divisions (n = 3 animals/group) are shown. (D) IFNγ ELISPOT production by Mar T cells stimulated with 10 μM HYDby plus spleen cells. (E) Proliferation of CFSE-labeled Vβ6+ Mar T cells 3 d after adoptive transfer into indicated mice (3 × 10⁶ cells/mouse). (Left) representative plots gated on CFSE Vβ6+ cells (inset: % Mar cells/spleen). (Right) quantified means (n = 3 animals/group). (F) Daf1−/− or Daf1+/+ mice were immunized with OVA323-339 plus anti-C5 mAb or control (1 mg i.p. every other day), and recall assays to OVA323-339 (0.1 μM) were performed by ELISPOT on d 16. *, P < 0.05 versus the response in Daf1−/− mice. Right: 3-d in vitro IFNγ ELISPOT assays of H-2k T cells versus Daf1+/+ or Daf1−/− APCs plus 100 μg/ml anti-C5 mAb or control (top) or H-2k T cells versus Daf1+/+ spleen cells plus recombinant C5a (bottom). *, P < 0.05 versus control. Each result is representative of three individual experiments.
Flow cytometry confirmed that all IFN were given adoptive transfers of 7.5 splenic T cells isolated from Thy1.2 ELISPOT assays (means plus SD; substituted hosts were immunized with HY cells in IFN immunity primed in vitro by immunization and partially blocked the augmented T cell alloimmunity in vitro (Fig. 3 F). in vitro cultures enhanced T cell responsiveness (Fig. 3 F).)

Because of the previously described findings implicating Daf in T cell responsiveness (Fig. 3 F), anti-C5 mAb partially abrogated the enhanced T cell proliferation and cytokine production in vitro culture supernatants as assessed by zymosan uptake assays (Fig. 5 C). Western blotting with specific antibodies further verified the complement component production by T cells as well as by APCs (Fig. 5 D).

Overall, our findings that (a) T cells proliferate into an expanded number of effector cells in the absence of Daf, (b) the effects of Daf deficiency are abrogated in the absence of factor D, (c) the augmented responsiveness is reduced by anti-C5 mAb, and (d) T cell responsiveness is increased by C5a uncover an important role for complement and Daf as modulators of T cell immunity. The precise mechanisms by which APC- and/or T cell–produced complement activation fragments participate in costimulation remains to be characterized fully. Although our data demonstrate a role for C5 (see Fig. 3 F) potentially through C5a, a finding consistent with previous reports that C5aR inhibition diminishes antiviral immunity (19), the molecular basis of complement–T cell interactions may be multifactorial. There are reports that CR1 blockade inhibits in vitro T cell activation (20–22), and there are reports that the absence of C3a receptor on APCs decreases Th1 immunity (23). Deposited C3b or other complement split products during T cell–APC interactions also could stimulate T cells during antigen-induced activation (21). Control experiments have shown Daf deficiency does not affect surface expression of costimulatory molecules on CpG-activated macrophages or DCs (unpublished data).

Enhanced T cell responsiveness in the absence of Daf potentially has several implications. In addition to the accelerated kinetics of rejection (Fig. 2), other studies have shown Daf deficiency does not affect surface expression of costimulatory molecules on CpG-activated macrophages plus HYDby peptide (but not OVA323–339; unpublished data). In accordance with the increased gene expression, stimulation of Mar T cells with HYDby–peptide–loaded macrophages induced C3 protein as detected by immunoelectron microscopy (Fig. 5 B). Antigen-specific T cell/APC mixing, as well as anti-CD3 stimulation of polyclonal T cells, generated C3, factor B, and factor D proteins in serum-free culture supernatants as assessed by zymosan C3b uptake assays (Fig. 5 C). Western blotting with specific antibodies further verified the complement component production by T cells as well as by APCs (Fig. 5 D).

Because of the previously described findings implicating complement, we next evaluated synthesis of alternative pathway complement components by T cells and APCs during cognate interactions. We established an MLR in serum-free medium, separated the T cells and APCs by flow sorting at different time points, and performed quantitative RT-PCR for C3, factor B, and factor D on each population. These studies showed that both T cells and APCs markedly up-regulated synthesis of all three components within 1 h of interaction (Fig. 5 A). Similar results were detected when Mar TCR transgenic T cells were stimulated with syngeneic macrophages plus HYDby peptide (but not OVA323–339; unpublished data). In accordance with the increased gene expression, stimulation of Mar T cells with HYDby–peptide–loaded macrophages induced C3 protein as detected by immunoelectron microscopy (Fig. 5 B).

Figure 4. Daf deficiency on T cells enhances T cell responsiveness. (A) Purified T cells were mixed with WT allogeneic H-2b splenic stimulator cells in IFN ELISPOT assays. (B) T cell–depleted WT Thy1.1 (H-2b) females were given adoptive transfers of 7.5 × 10^6 unfractionated, purified splenic T cells isolated from Thy1.2+ Daf1+/+ or Daf1−/− mice. The reconstituted hosts were immunized with HYDby plus CFA, and recall IFN ELISPOT assays (means plus SD; n = 3/group) were performed 21 d later. Flow cytometry confirmed that all IFNγ derived from the Thy1.2+ cells (not depicted). *, P < 0.05.

Because the absence of Daf disables cell-surface C3 and C5 convertase regulatory activity, and because there is a report that C5a can influence T cell immunity (19), we tested whether C5 is involved in the enhanced T cell responsiveness. As shown in Fig. 3 F, anti-C5 mAb partially abrogated the enhanced in vivo T cell responsiveness in Daf1−/− mice after immunization and partially blocked the augmented T cell alloimmunity primed in vitro by Daf1−/− APCs. Addition of C5a to in vitro cultures enhanced T cell responsiveness (Fig. 3 F).

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Enhanced T cell responsiveness in the absence of Daf potentially has several implications. In addition to the accelerated kinetics of rejection (Fig. 2), other studies have shown that MOG35–55–induced experimental autoimmune encephalomyelitis is more severe in Daf1−/− mice, indicating that Daf may be important in T cell autoimmunity (unpublished data). Our data reveal that the augmented immunity persists for at least 30 d (Fig. 2), but we have not yet fully addressed the longevity of the memory response.

Although our data generated in Daf1−/− mice implicate that Daf is important in T cell responsiveness via effects on complement activation, the physiological mechanism is not established. Flow cytometric analysis showed down-regulated surface expression of Daf on APCs during antigen-spe-
Figure 5. T cells and APCs produce complement components during cognate interactions. (A) H-2k T cells were mixed with allogeneic peritoneal macrophages, flow sorted at predetermined time points, tested for complement expression by quantitative RT-PCR, and compared with unstimulated controls. (B) Electron micrograph of immunostaining using gold–anti-C3 of Mar T cells mixed with female H-2b peritoneal macrophages plus HYDby peptide (top) or OVA323-339 (bottom). Note gold particles (arrowheads) only in the HYDby peptide-stimulated sample. T, T cell; M, macrophage. Bar, 200 μm. (C) C3, factor B, and factor D in serum-free culture supernates of Mar T cells mixed with HYDby-loaded APCs overnight before (top) and after (middle) cell sorting and reculturing for an additional 3 h. Data are plotted as relative increase over OVA323-339-stimulated controls. C3, factor B, and factor D in serum-free culture supernates of H-2k T cells stimulated overnight with anti-CD3 (bottom panel), expressed as fold increase over controls. (D) Western blots for factor B (fB, top) and C3 (bottom) in culture supernates of H-2k T cells stimulated overnight with anti-CD3, expressed as fold increase over controls. (E) Plots of Daf expression on macrophages at 0, 24, and 48 h after mixing with Mar T cells plus HYDby peptide versus OVA323-339. All results are representative of experiments performed at least two or three times.
cific, cognate interactions between Marilyn (Mar) T cells and macrophages (see Fig. 5 E). These findings are consistent with previously reported analyses (24) that, after superantigen administration, isolated splenic T cell mRNAs for common T cell–signaling molecules were markedly increased at 8 h, but mRNA for Daf was decreased 10-fold.

In summary, in addition to providing a possible explanation for previous reports (2–4, 6, 21, 23, 25), our data raise the possibility that Daf expression could be genetically or pharmacologically manipulated for therapeutic purposes.

MATERIALS AND METHODS

Mice. Daf1−/− (H-2b) mice and littermate controls backcrossed to C57BL/6 four or nine generations were produced as described previously (25). Factor D−/− mice were intercrossed with the Daf1−/− mice. Female Mar-Rag2−/− mice (H-2b; reference 26) were a gift from P. Matzinger (National Institutes of Health, Bethesda, MD). Remaining mice were purchased from Jackson Immunoresearch Laboratories. Animals were used under approved animal protocols. Skin graft transplantation was performed as described previously (27, 28).

IFNγ ELISPOT assays. Cytokine-secreting spleen or purified T cells (>93% CD3+; columns obtained from R&D Systems) were quantified by IFNγ or IL-2 ELISPOT as described previously (27, 28) with or without anti-C5 mAb (clone BB5.1; Alexion), anti-Daf mAb (25) (2C6; B.P. Morgan, Cardiff University, Cardiff, Wales, UK), isotype control, or recombinant mouse C5a (Cell Sciences). Daf expression was reconstituted on Daf1−/− cells using a lipid-tailed Daf molecule (N-(myristoyl)GSSKSPS-KKKKKKPGDC-(S-2-thiophenyldiyl) C-amide (R.A.G. Smith, Inflazyme Pharmaceuticals, Richmond, BC, Canada) added to the free carboxyl-terminal Cys of mouse Daf CCP1-4 (supplemental text is available at http://www.jem.org/cgi/content/full/jem.20041967/DC1). Peptides were synthesized by Research Genetics. In vitro experiments were performed in serum-free HL-1 medium (Cambrex Bioproducts).

Proliferation assays. CFSE-stained T cells (27) were mixed with spleen cells or thioglycollate-induced peritoneal macrophages. For in vivo stimulation, 3 × 106 CFSE-labeled cells were injected into the tail vein of sublethally irradiated (400 rad) mice and analyzed 3 d later. The percentage of responding cells was calculated as described previously (27). All other antibodies were obtained from BD Biosciences. Cells were harvested on day 2, 3, and 4 and analyzed on a Becton Dickinson FACScan.

In vivo T cell transfer and immunization. Female C57BL/6 Thy1.1 (Daf1−/−) mice CD4+ and CD8-depleted with GK1.5/YTS 191 plus TIB 105/YTS 169.4 on days −3, −2, and −1. 7.5 × 106 Daf1−/− or Daf1+−/− (both Thy 1.2) T cells were adoptively transferred (tail vein) on day 0. Mice were immunized on day 1 using 1 μg of HYDβy peptide in CFA.

Immunoelectron microscopy. Peritoneal macrophages were placed in 0.4-μm tissue culture inserts (Becton Dickinson) in 24-well culture dishes with Mar T cells at a 1:1 ratio, with or without HYDβy peptide or control OVA253-33 peptide at 10 μg/ml. After fixation with 1% paraformaldehyde/0.1% glutaraldehyde/PBS/0.05 M sucrose, samples were dehydrated, embedded, sectioned, labeled with goat anti–mouse C3 (MP Biomedicals, Inc.), and gold-labeled donkey anti–goat IgG (Jackson Immunoresearch Laboratories). Counterstaining was performed with lead citrate.

Quantitative analysis of complement components in T cells and macrophages. Total RNA was extracted from the sorted populations of T cells and macrophages (Qiagen mini RNeasy kit) and reverse transcribed by oligo dT primer with SuperscriptII reverse transcriptase (Invitrogen). Real-time PCR was performed on an Applied Biosystems Prism 7700 Sequence Detection System with respective primers (available from author by request). The average threshold cycle differences among the samples were normalized against β-actin (control) in the corresponding cDNA preparation.

Complement assays. Supernatants were obtained from overnight cultures of purified T cells with or without anti-CD3 (2C11, 2 μg/ml) or CFSE-labeled Mar T cells plus peptide/APCs in serum-free medium. CFSE-labeled Mar T cells were flow sorted and incubated for an additional 3 h at 37°C. The supernates were added to C3-, factor B-, or factor D-deficient mouse sera, and C3b uptake on zymosan granules was quantified by flow cytometry after staining with FITC-labeled polyclonal anti–mouse C3 (25). Western blots were performed as described previously (22), see supplemental Materials and methods.

Statistical analysis. Statistical analysis to determine differences between groups for recall immune responses was performed using the Student’s t test. P < 0.05 was considered statistically significant.

Online supplemental material. Details of the methods for preparation of lipid-tailed Daf and Western blots for complement components in culture supernatants are available online or from the author by request. Online supplemental material is available at http://www.jem.org/cgi/content/full/jem.20041967/DC1.

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Preparation of lipid-tailed Daf. A lipid tail was added to mouse Daf CCP1-4 Cys by derivatization at the free carboxyl-terminal cysteine with the sulfhydryl-reactive peptide, N-[(myristoyl)GSKPSKKKKKPGDC-(S-2-thiopyridyl)] C-amide (termed APT542; provided by R.A.G. Smith, Inflazyme Pharmaceuticals, Vancouver, Canada). In brief, to produce the lipid-tailed Daf, mDaf CCP1-4 Cys (prepared in Pichia Pastorias and affinity purified over a nickel sepharose column) was treated with 1 mM TCEP overnight at room temperature followed by incubation with the lipid tail APT542. Coupling efficiency was checked by SDS-PAGE and the uncoupled lipid tail was removed by dialysis against PBS. To incorporate the resulting lipid-tailed Daf into splenocytes, 10 µl of the prepared lipid-tailed Daf and/or control PBS alone were mixed with 50 × 10⁶ freshly isolated spleen cells in HL-1 medium and incubated at room temperature for 1 h. After incubation, spleen cells were washed two times and incorporation of the lipid-tailed Daf was verified by flow cytometry with anti-mDaf mAb 2C6. Control experiments with antibody-sensitized sheep erythrocytes documented that the lipid-tailed molecule stayed associated with the erythrocytes and inhibited mouse C3b uptake 50-60-fold more efficiently than the soluble molecule (unpublished data).

Western blots. Western blots were performed on nonreducing 7.5% SDS-PAGE gels with proteins transferred and the electrophoresed proteins were transferred to polyvinylidifluoride membranes. The blots were probed with polyclonal goat anti-mouse C3 (ICN Biomedicals) or with polyclonal rabbit anti-human factor B (Calbiochem). The blots were developed with horseradish peroxidase-labeled rabbit anti-goose or goat anti-rabbit IgG (DakoCytomation) followed by enhanced chemiluminescence (Amersham Biosciences). 1–500 diluted sera from wild-type, C3⁻/⁻, and factor B⁻/⁻/Crry⁻/⁻ mice (H-2b; supplied by H. Molina, Washington University, St. Louis, MO) were used as positive and negative controls.