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BAFF- and APRIL-Dependent Maintenance of Antibody Titers after Immunization with T-Dependent Antigen and CD1d-Binding Ligand

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CD1d-restricted invariant NKT (iNKT) cells boost humoral immunity to T-dependent Ags that are coadministered with the CD1d-binding glycolipid Ag α-galactosylceramide (α-GC). Observations that mice lacking iNKT cells have decaying Ab responses following vaccination have led to the hypothesis that iNKT cells express plasma cell (PC) survival factors that sustain specific Ab titers. Bone marrow chimeric mice in which the entire hematopoietic compartment or iNKT cells selectively lacked BAFF, a proliferation-inducing ligand (APRIL), or both BAFF and APRIL were created and immunized with nitrophenol hapten-conjugated keyhole limpet hemocyanin adsorbed to Imject aluminum hydroxide–containing adjuvant or mixed with α-GC. In comparison with BAFF- or APRIL-sufficient bone marrow chimeras, absence of hematopoietic compartment- and iNKT-derived BAFF and APRIL was associated with rapidly decaying Ab titers and reduced PC numbers. The iNKT cell–derived BAFF or APRIL assumed a greater role in PC survival when α-GC was used as the adjuvant for immunization. These results show that iNKT cell–derived BAFF and APRIL each contribute to survival of PCs induced by immunization. This study sheds new light on the mechanisms through which iNKT cells impact humoral immunity and may inform design of vaccines that incorporate glycolipid adjuvants. The Journal of Immunology, 2013, 191: 000–000.

Abbreviations used in this article: Alum, Imject aluminum hydroxide–containing adjuvant; APRIL, a proliferation-inducing ligand; B6, C57BL/6; BCMA, B cell maturation Ag; BM, bone marrow; DC, dendritic cell; DKO, double knockout; α-GC, α-galactosylceramide; iNKT, invariant NKT; KLH, keyhole limpet hemocyanin; LLPC, long-lived plasma cell; NP, 4-hydroxy-3-nitrophenyl acetyl; PC, plasma cell; Tg, transgenic.

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APRIL are each critical to the establishment and/or survival of BM-resident PCs (21). BAFF and APRIL are not essential for memory B cell survival (22).

BAFF- and APRIL-encoding mRNA have been detected following microarray analysis of murine iNKT cells (23, 24). We therefore tested the hypothesis that iNKT cell–derived BAFF and/or APRIL regulate PC survival. To achieve this goal, BM chimeric mice were generated in which the entire hematopoietic system or iNKT cells selectively lacked expression of BAFF, APRIL, or both. We show that iNKT cell–derived BAFF and APRIL are individually dispensable for induction and maintenance of α-GC–enhanced Ab responses. When both BAFF and APRIL are absent, induction of Ab responses is intact, but the titers decay more rapidly than in wild-type controls or in mice singly deficient for BAFF or APRIL. We have therefore uncovered part of the mechanism by which iNKT cells impact the maintenance of humoral immunity.

Materials and Methods

Mice

Female B6 mice (CD45.2- and CD45.1-congenic) were purchased from the National Cancer Institute (Bethesda, MD). Jα18−/− mice have a gene deletion in the TCR locus preventing rearrangement of type I NKT cell α-GC–reactive TCR (25) and were provided by Dr. M. Kronenberg (La Jolla Institute for Allergy and Immunology, La Jolla, CA). Jα18−/− mice were maintained at University of Oklahoma Health Sciences Center. All procedures were approved by the Institutional Animal Care and Use Committee at University of Oklahoma Health Sciences Center. BAFF−/− (26), APRIL−/−, and BAFF−/−/APRIL−/− (double knockout, DKO) mice on a homogeneous B6 (CD45.2) genetic background (at least nine backcrosses) were maintained at the University of Southern California (Los Angeles, CA) with Institutional Animal Care and Use Committee approval.

FIGURE 1. B cells and NKT cells in donor mice. BM cells and splenocytes were harvested from the donor B6, Jα18−/−, BAFF−/−, APRIL−/−, and DKO mice (n = 3–5/group). (A) BM cells were analyzed by flow cytometry for B220+ versus CD93+ mature B cells. (B) Splenocytes were analyzed by flow cytometry for TCRb+ versus CD1d tetramer+ cells. (C) Mean ± SD frequency; (D) absolute numbers ± SD of NKT cells. (E and F) Splenocytes from B6, Jα18−/−, BAFF−/−, APRIL−/−, and DKO mice were stimulated in vitro with α-GC and incubated for 48 h before collecting supernatants and measuring (E) IL-4 and (F) IFN-γ by ELISA. Data show means ± SD for triplicate samples. Data shown in (A)–(F) are representative of two independent experiments.
proval. Long bones and spleens were harvested and shipped to University of Oklahoma Health Sciences Center overnight in ice-cold media. Cells were then prepared and used for experiments. Vo14 TCR transgenic (Tg) mice were purchased from The Jackson Laboratory (Bar Harbor, ME).

Reagents

HRP-conjugated anti-IgG1 was from SouthernBiotech (Birmingham, AL). Fluorochrome-conjugated mAbs were from BD Biosciences (San Jose, CA). FcYR-blocking mAb (2.4G2) was from Bio X Cell (West Lebanon, NH). CD1d tetramers loaded with α-GC analog PBS37 were provided by the National Institute of Allergy and Infectious Diseases Tetramer Facility (Emory University, Atlanta, GA). Recombinant BAFF and APRIL, BAFF- and APRIL-specific Ab and blocking peptides, and α-GC were from Axxora (San Diego, CA). Imject aluminum hydroxide–containing adjuvant (Alum) was from Pierce (Rockford, IL). iNKT hybridoma cells (NKT.3c3) were provided by Dr. Mitchell Kronenberg (La Jolla Institute for Allergy and Immunology, La Jolla, CA).

SDS-PAGE and immunoblotting

Cell lysates were subjected to SDS-PAGE and immunoblotting using standard procedures. ECL Plus reagent (GE Healthcare, Piscataway, NJ) was used to detect membrane-bound Ab and imaged using a FluorChem Q imager (Alpha Innotech, Santa Clara, CA).

BM chimeras

Six-week-old female B6 CD45.1 mice were irradiated (700 rad) and rested for 18 h before a second irradiation (500 rad). After a further 4 h, 10⁶ CD45.2-expressing donor BM cells were transferred i.v. to the recipients. The single donor chimeras consisted of BM from B6, BAFF+/−, APRIL+/−, or DKO mice. The mixed donor chimeras consisted of the following 50:50 mixtures: Jα18−/−/Jβ, Jα18−/−/BAFF−/−, Jα18−/−/APRIL−/−, or Jα18+/−/DKO−/−. Recipients were housed for 12 wk before confirming engraftment and commencing experiments.

Isolation of splenocytes, BM, and iNKT cells

Splenocytes and BM cells were obtained as described previously (11). Cells were enumerated using a cell counter from Nexcelom Bioscience (Lawrence, MA). The iNKT cells were isolated by magnetic sorting using PE-B220-based negative selection followed by allophycocyanin-CD1d-tetramer–based positive selection. This was done according to the manufacturer’s instructions (Miltenyi Biotec, Auburn, CA). Purity and yield were measured using cell counting and flow cytometry.

Flow cytometry

Cells were incubated at 4°C or room temperature at a density of 10⁷ cells/ml in RPMI 1640 plus 10% FCS with 2.4G2 mAb at a final concentration of 20 μg/ml. Fluorochrome-conjugated mAbs were added at a 2–10 μg/ml final concentration as appropriate or with allophycocyanin-conjugated CD1d tetramer at a 4 μg/ml final concentration. After 1 h, unbound mAb or tetramer was removed by washing and centrifugation. Cells were fixed with 1% (w/v) paraformaldehyde and analyzed using a FACScalibur and BD Accuri cytometers (BD Biosciences, Palo Alto, CA). Forward and side scatter gating was used to select live splenocytes and bone marrow cells. The iNKT cell and mature B cell populations were then determined by anti-TCRβ/CD1d-tetramer and anti-B220/anti-CD39 staining respectively.

Cytokine assays

Two hundred microliters of splenocytes at a density of 10⁷ cells/ml was added to round-bottom sterile microtiter plates and followed by addition of media or media containing α-GC at a final concentration of 50, 250, or 500 ng/ml. Plates were incubated under 5% CO₂ for 6–48 h before collection of supernatants, which were stored at −80°C until required. IL-4 and IFN-γ concentrations were measured using multiplex cytokine assay kits (Millipore, Bedford, MA) in conjunction with Bio-Plex instrumentation (Bio-Rad, Mountain View, CA). BAFF concentrations were measured by ELISA using a commercially available kit (R&D Systems, Minneapolis, MN).

Immunization schedule

As described previously (10–12, 27) a single s.c. immunization consisting of 10 μg 4-hydroxy-3-nitrophenyl acetyl (NP)–keyhole limpet hemocyanin (KLH) in 200 μl sterile-endotoxin-free PBS, NP-KLH mixed with 100 μl PBS and 100 μl Alum, or NP-KLH mixed with 4 μg α-GC was administered over both flanks. Mice were bled on day 28 and then boosted s.c. with 10 μg NP-KLH in PBS and bled on days 35, 61, and 91. At the end of the experiment, mice were euthanized to obtain BM.

Serum Ig measurement

Mice were bled and serum samples were prepared and stored at −20°C until required. End point NP-specific Ig titers (greatest serum dilution at which reactivity with Ag could not be detected) were then determined by ELISA as described previously (11). Ab titers were plotted using GraphPad Prism 5.0 software.

ELISPOTs

ELISPOTs were performed as described previously (11). Spots, corresponding to Ab-secreting cells, were enumerated using a KS ELISPOT 4.10 plate reader (Carl Zeiss, Thornwood, NY).

Statistical analysis

GraphPad Prism 5 software (GraphPad Software, La Jolla, CA) was used for statistical analysis. A nonparametric Mann–Whitney U test was used to assess experiments with two experimental groups (or multiple groups with independent matched controls), which provides an exact p value. Multiple experimental groups were assessed by one-way ANOVA with a Dunn posttest. Comparisons of pairs of groups in the Dunn posttest indicate a p value within a range.

Results

Characterization of iNKT cells in BAFF+/−, APRIL+/−, and DKO mice

BAFF+/− mice are well recognized to have defects in the development and survival of mature B cells, whereas APRIL+/− mice...
have normal B cell maturation (20). B220+/CD93− mature B cells in the BM of B6, Jα18−/−, BAFF−/−, APRIL−/−, and DKO mice were analyzed by flow cytometry (Fig. 1A). B6 and Jα18−/− mice had comparable frequencies of mature B cells, whereas BAFF−/− mice had fewer mature B cells. APRIL−/− mice had normal B cell frequencies whereas DKO mice had a low frequency of mature B cells, similar to the BAFF−/− mice.

Splenic iNKT cells were analyzed by flow cytometry and found to be intact across all the strains except Jα18−/− mice (Fig. 1B–D). Similarly, the functional capacity of iNKT cells in the BAFF−/−, APRIL−/−, and DKO mice was intact as demonstrated by secretion of IL-4 and IFN-γ in response to in vitro stimulation of splenocytes with α-GC (Fig. 1E, 1F). Differences in number of iNKT cells were expected because variances in B cells affect the relative proportion of iNKT cells in the mixed splenocytes and therefore affect the absolute amounts of IL-4 and IFN-γ produced.

Absence of BAFF and APRIL in the hematopoietic compartment is associated with rapid decline of specific Ab titers

Single-donor BM chimeras were generated whereby the hematopoietic compartment was able to express both BAFF and APRIL (B6 chimera), selectively lacked BAFF (BAFF−/− chimera) or APRIL (APRIL−/− chimera), or lacked both BAFF and APRIL (DKO chimera) (Fig. 2). This was achieved by engrafting irradiated CD45.1-expressing mice with CD45.2-expressing donor BM cells. BM B220+/CD93− mature B cells were restored comparably in all chimeras (Fig. 2A). NKT cells were comparably restored in all chimeras except the DKO, which had a higher splenic iNKT frequency (Fig. 2B). Total numbers of spleen and BM cells recovered from each chimera were similar, and thus B cell and NKT cell frequencies were reflective of total cell numbers. CD45.2+ donor-derived cells constituted ≥95% of the reconstituted lymphocytes in the spleen, consistent with our previous work (data not shown) (14, 27). CD4+ T cells, CD8+ T cells, and DCs were also comparably restored (data not shown).

Prior to immunization with NP-KLH/Alum or NP-KLH/α-GC, anti-NP IgG1 titers could not be detected in the serum of the single chimeras (not depicted).

Absence of BAFF and APRIL in the hematopoietic compartment is associated with rapid decline of specific Ab titers

Single-donor BM chimeras were generated whereby the hematopoietic compartment was able to express both BAFF and APRIL (B6 chimera), selectively lacked BAFF (BAFF−/− chimera) or APRIL (APRIL−/− chimera), or lacked both BAFF and APRIL (DKO chimera) (Fig. 2). This was achieved by engrafting irradiated CD45.1-expressing mice with CD45.2-expressing donor BM cells. BM B220+/CD93− mature B cells were restored comparably in all chimeras (Fig. 2A). NKT cells were comparably restored in all chimeras except the DKO, which had a higher splenic iNKT frequency (Fig. 2B). Total numbers of spleen and BM cells recovered from each chimera were similar, and thus B cell and NKT cell frequencies were reflective of total cell numbers. CD45.2+ donor-derived cells constituted >95% of the reconstituted lymphocytes in the spleen, consistent with our previous work (data not shown) (14, 27). CD4+ T cells, CD8+ T cells, and DCs were also comparably restored (data not shown).

Prior to immunization with NP-KLH/Alum or NP-KLH/α-GC, anti-NP IgG1 titers could not be detected in the serum of the single chimeras (not depicted).
Following immunization of the single chimeras with NP-KLH/Alum, anti-NP IgG1 titers were detectable after 28 d (Fig. 3A–D). When a booster vaccine was given consisting of NP-KLH alone, the titers were further increased. This is consistent with published reports that BAFF and APRIL are individually (28) and collectively (22) dispensable for Ab recall responses. Comparable anti-NP IgG1 titers were typically observed for the single chimeras on day 35 (7 d after booster vaccine administration) (Fig. 3A–D). The large Ab titers in the absence of BAFF were consistent with a previous demonstration that radiation-resistant stromal cells provide sufficient BAFF to support engraftment and function of BAFF−/− donor cells (29). In the B6, BAFF−/−, and APRIL−/− chimeras, the end point titers displayed a nonsignificant decline during the next 56 d (day 91 after initial immunization) (Fig. 3A–C). In contrast, the DKO chimeras showed a dramatic and significant (93.7%) decline in end point IgG1 titer by day 61 (Fig. 3D). The decline in IgG1 titers in the DKO chimeras was not compensated by increases in other IgG subclasses, including IgG2b and IgG2c, which had much lower titers than IgG1 (data not shown).

Following immunization of the single chimeras with NP-KLH/α-GC, all groups had measurable primary IgG1 titers before administration of the booster vaccine on day 28 (Fig. 3E–H). APRIL−/− and DKO chimeras, but not BAFF−/− chimeras, had lower titers than did the B6 controls, suggesting a contribution of APRIL to α-GC–driven primary Ab responses (p = 0.01–0.05). All groups had a similar anti-NP IgG1 titer on day 35 (Fig. 3E–H), showing that BAFF and APRIL were individually and collectively dispensable for α-GC–driven Ab recall responses. The end point titers modestly declined over the subsequent 56 d in the B6, BAFF−/−, and APRIL−/− chimeras, but the differences were not significant (Fig. 3E, 3F). In DKO chimeras, however, the IgG1 titers showed a dramatic (82.5%) and statistically significant decline by day 91 (Fig. 3H).

To establish that a decline in Ab titer was attributable to lack of PC persistence, BM cells were assessed at the end of the experiment for cells secreting NP-specific IgG1. The number of NP-specific PCs at day 95 in the DKO chimeras immunized with NP-KLH/Alum (Fig. 4A) or NP-KLH/α-GC (Fig. 4B) was lower than in the B6 chimeras. ELISPOT analysis was confined to the BM because very few splenic PCs can be detected 3 mo after immunization (11). These results collectively show that the maintenance of immunization-induced PCs and serum Ab titers were highly dependent on the expression of BAFF and APRIL whether Alum or α-GC was used as the adjuvant.

**FIGURE 5.** Expression of BAFF and APRIL by splenic iNKT cells. (A) NKT.3c3 hybridoma cell lysates (2.4, 1.2, and 0.6 × 10⁶ cell equivalents per lane) were resolved by SDS-PAGE and transferred to nitrocellulose membranes before immunoblotting for BAFF (upper panels) and APRIL (lower panels). Recombinant murine soluble BAFF (rms BAFF) served as a positive control for BAFF expression. Membranes were also prepared and incubated with anti-BAFF or anti-APRIL alone or in combination with a 100-fold molar excess of blocking peptide. (B) B6 mice were immunized i.p. with PBS or PBS containing α-GC. After 16 h, splenocytes were harvested and lysates prepared before immunoblotting as indicated. (C) B6 mice were immunized i.p. with α-GC or PBS vehicle before collecting splenocytes, culturing for 6 h, and measuring BAFF by ELISA. Data show means ± SD (n = 6). Data are pooled from two experiments. (D) Splenocytes were obtained from Jα18−/−, B6, and Vα14 Tg mice and analyzed by flow cytometry (dot plots) or cultured before collecting supernatants and measuring BAFF concentrations by ELISA (bar graph). Values in bar graph represent means ± SD for triplicate samples and are representative of two independent experiments. (E) Dot plot shows isolated INKT cells and graph shows mean ± SD concentrations of secreted BAFF (for duplicate samples) following culture of cells with media or media containing PMA/ionomycin. Data are representative of three independent experiments. **p = 0.001–0.01.
BAFF and APRIL expression by iNKT cells

Expression of BAFF and APRIL was examined before and after iNKT cell activation (Fig. 5). Mouse hybridoma iNKT cell (3C3) lysates were analyzed by SDS-PAGE, and immunoblotting revealed constitutive expression of BAFF and APRIL (Fig. 5A). Blocking peptides confirmed the specificity of the Abs used.

Splenocytes were collected from B6 mice after injection with PBS or PBS/α-GC. Splenic cell lysates were prepared and analyzed for BAFF and APRIL expression (Fig. 5B). Constitutive expression was detected and α-GC treatment led to increased expression relative to two loading controls (IgM and β-actin). B6 mice were also immunized with PBS or α-GC before collecting splenocytes for culture and measuring secreted BAFF by ELISA. BAFF concentrations were modestly (~30%) but significantly higher in splenocyte cultures from α-GC–treated mice than from PBS-treated mice (Fig. 5C).

Unfortunately, Abs claimed to detect BAFF or APRIL by flow cytometry were not specific, as were reagents to detect APRIL by ELISA. Detection of secreted BAFF in B6 mice also proved difficult owing to low iNKT numbers rather than to reagent specificity. We therefore compared iNKT cell numbers in Jα18–/–, B6, and Vα14 TCR Tg mice (Fig. 5D). As expected, iNKT cells were nearly absent in Jα18–/– splenocytes (0.02%), detectable in B6 splenocytes (1.09%), but accounted for 8.78% of Vα14 TCR Tg splenocytes. Culturing splenocytes from these mouse strains revealed that constitutive BAFF secretion correlated with the NKT cell frequency. Treatment with α-GC in vitro did not increase BAFF secretion (data not shown). Importantly, BAFF secretion by iNKT cells isolated from Vα14 TCR Tg mice increased following stimulation with PMA/ionomycin (Fig. 5E). The data collectively show that splenic iNKT cells could increase BAFF expression following activation.

We then obtained bone marrow cells from Jα18–/–, B6, and Vα14 TCR Tg mice and examined iNKT cell frequency (Fig. 6A). The iNKT cells were nearly absent in samples from the Jα18–/– mice (0.04%) and detectable in samples from the B6 mice (0.29%). The iNKT cells accounted for 2.65% of the cells in samples from the Vα14 TCR Tg mice. BM cells were then cultured with vehicle, α-GC, or PMA/ionomycin (Fig. 6B, 6C). Treatment in vitro did not increase BAFF secretion in the BM cells from Jα18–/– or B6 mice (Fig. 6B). Constitutive BAFF secretion was highest in the cultures from Vα14 TCR Tg mice (Fig. 6B). Treatment in vivo also did not induce BAFF secretion from the B6 BM cells (data not shown).

In contrast, treatment in vitro with α-GC led to a modest but significant increase in BAFF secretion by cells derived from the Vα14 TCR Tg mice (Fig. 6B, 6C). As compared with α-GC treatment, a larger response was evident when PMA/ionomycin were used for treatment (Fig. 6C, 6D). The PMA/ionomycin treatment was also used to demonstrate specificity of the reagents by culturing BM cells from the BAFF–/–, APRIL–/–, and DKO–/– donor mice (Fig. 6D). As expected, BAFF was not secreted by cells from BAFF–/– or DKO donor mice. BAFF secretion by the APRIL–/– mice appeared lower than in the B6 or Jα18–/– BM cells, but ANOVA comparison of all PMA/ionomycin-stimulated groups did not detect significant differences.

BAFF secretion was not detected in BM NKT cells isolated from Vα14 Tg mice by FACS and cultured with or without PMA/ionomycin (data not shown). The data therefore suggest that BM iNKT cells do not express BAFF directly, but potentiate its production by other cell types in the BM, because higher NKT cell numbers were associated with more BAFF secretion.

Absence of iNKT cell–derived BAFF and APRIL is associated with rapid decline of specific Ab titers

Mixed-donor BM chimeras were generated in which iNKT cells were able to express both BAFF and APRIL (Jα18–/–/B6), selectively lacked BAFF (Jα18–/–/BAFF–/–) or APRIL (Jα18–/–/APRIL–/–), or lacked both BAFF and APRIL (Jα18–/–/DKO). This was achieved by engrafting irradiated CD45.1-expressing mice with a 50:50 mix of CD45.2-expressing Jα18–/– and either 1) B6, 2) BAFF–/–, 3) APRIL–/–, or 4) DKO donor cells. As demonstrated in our previous studies using mixed chimeras (14, 27, 30), major immune cell types including B cells, CD4+ T cells, and CD8+ T cells,...
CD8+ T cells, and DCs were reconstituted equally across experimental groups (data not shown). BM and spleen showed comparable restoration of B220+CD93- mature B cells (Fig. 7A) and iNKT cells, respectively (Fig. 7B). Furthermore, >95% of reconstituted cells, including iNKT cells, were donor-derived CD45.2+ cells (data not shown). Therefore, hematopoietic compartment-derived BAFF could not be produced by iNKT cells in the Jα18-/-/DKO chimeras. Similarly, iNKT cells could not produce APRIL in Jα18-/-/APRIL-/- chimeras nor could they produce BAFF or APRIL in Jα18-/-/DKO chimeras.

As expected, each of the mixed chimeras immunized with NP-KLH/Alum generated primary anti-NP IgG1 titers that were significantly boosted by later (day 28) administration of NP-KLH alone. Consequently, 35 d following immunization with NP-KLH/Alum (Fig. 8A–D), each of the mixed chimeras had similar NP-specific IgG1 titers. Again, IgG1 was the dominant Ab subclass produced (data not shown). Sera were collected from each chimera on days 61 and 91 after immunization and titers compared with the “starting” IgG1 titers on day 35. In the NP-KLH/Alum-immunized chimeras, the IgG1 titers were sustained in all groups (Fig. 8A–D). These results indicated that NKT-derived BAFF and APRIL did not play a major role in persistence of Ab responses following NP-KLH/Alum immunization.

End point anti-NP IgG1 titers were also monitored in chimeras immunized with NP-KLH/α-GC (Fig. 8). In the Jα18-/-/B6 and the Jα18-/-/BAFF-/- groups, the primary IgG1 titers were boosted by immunization with NP-KLH alone on day 28 and did not exhibit significant decreases from day 35 to day 91 (Fig. 8E, 8F). In contrast, in the Jα18-/-/APRIL-/- and the Jα18-/-/DKO groups, also boosted on day 28, titers significantly declined between days 35 and 91 by 71 and 88.6%, respectively (Fig. 8H).

To confirm that the reduction in serum Ab titers was due to declining PC numbers, ELISPOT analyses were performed on day 95. The numbers of PCs in the BM in the Jα18-/-/DKO groups were compared. Following NP-KLH/Alum immunization, PC numbers were significantly lower in the Jα18-/-/DKO group than in the Jα18-/-/B6 and Jα18-/-/DKO groups. Surprisingly, similar results were observed for the NP-KLH/α-GC–immunized mixed chimeras (Fig. 9B), but PC numbers were dramatically (and significantly) lower in the Jα18-/-/DKO group than in the Jα18-/-/B6 controls. Collectively, these results indicate that iNKT-derived BAFF and APRIL contribute substantially to the maintenance of

**FIGURE 7.** Reconstitution of immune cell compartments in BM chimeras lacking BAFF and APRIL in the inNKT compartment. (A) BM cells were harvested from reconstituted chimeras and analyzed by flow cytometry. Graph depicts B220+CD93- cells as a percentage of total BM-derived cells. (B) Splenocytes were harvested from reconstituted chimeras and analyzed by flow cytometry. Graph depicts CD45.2+ anti-TCRβ- and CD1d tetramer-binding cells as a percentage of total splenocytes. Total BM cell and splenocyte recovery was comparable across all groups (not depicted). Data show mean ± SD values for analyses using three to five mice per group.

**FIGURE 8.** Immunization-induced Ab titers in chimeras lacking NKT-derived BAFF and APRIL. Sera were collected from the (A–D) NP-KLH/Alum–immunized and (E–H) NP-KLH/α-GC–immunized chimeras on the days indicated. Samples were analyzed by ELISA and end point anti-NP IgG1 titers were determined. Data show mean end point titers ± SD. Checkered bars indicate sera collected before the booster vaccine, whereas filled bars represent sera collected after the booster. Titers in prebleed sera were <1/200 (not depicted). Numbers of mice per group were: (A), (D), (E), and (H), n = 7–11; (B), (C), (F), and (G), n = 4–6. Statistically significant differences between experimental groups were determined by one-way ANOVA and a Dunn posttest. *p = 0.01–0.05, **p = 0.001–0.01, ***p < 0.001.
PC frequency and Ab titers following immunization with Ag mixed with α-GC, and perhaps following immunization with Ag adsorbed to Alum.

Discussion
To our knowledge, we report for the first time that iNKT cell–derived and –dependent BAFF and APRIL contribute to the maintenance of immunization-induced Ag-specific PCs. BAFF and APRIL derived from BM stromal cells as well as myeloid and lymphoid cells contribute to maintenance of PCs in the BM (29, 31). Coimmunization of mice with T-dependent Ag plus α-GC led to induction of LLPCs (11). In the absence of iNKT cells, Jα18−/− mice were unable to sustain long term-Ab titers following immunization with Ag plus α-GC (7). We therefore hypothesized that iNKT cell–derived BAFF and APRIL could account for iNKT cell–induced LLPCs.

Single BM chimeras were generated where the reconstituted hematopoietic compartment was competent for BAFF and APRIL expression, selectively lacked BAFF, selectively lacked APRIL, or lacked both BAFF and APRIL. When BAFF and APRIL were both absent, Ab titers and PCs were not sustained regardless of whether Alum or α-GC was used as the adjuvant. This observation is important because it reveals that the mechanisms by which iNKT cells contribute to PC survival are BAFF- and APRIL-dependent, regardless of their cellular source.

Mixed chimeras were generated in which iNKT cells lacked the ability to secrete BAFF, APRIL, or both BAFF and APRIL. In these mixed chimeras, iNKT cell–derived BAFF and APRIL, individually, were redundant for PC survival following immunization with Ag/Alum. In the absence of iNKT cell–derived BAFF and APRIL, the results were less clear. Ab titers did trend downward but the differences between the Jα18−/−/DKO group and the Jα18−/−/B6 controls were not statistically significant. However, ELISPOT analysis of BM cells revealed significant differences between groups. Statistical versus biological significance aside, there could be interesting explanations for the apparent discrepancy. For example, there could be a residual population of PCs in spleen supported by a non–iNKT cell source of BAFF and/or APRIL that helps to maintain Ab titers. Alternatively, the few PCs remaining in BM could secrete more Ab per cell and help to sustain Ab titers.

In contrast, when iNKT cells were unable to express APRIL alone or both BAFF and APRIL, Ag-specific Ab titers were not sustained following immunization with Ag/α-GC. The difference in decline of Ab titers did not differ significantly between APRIL−/− iNKT cells and DKO iNKT cells. This suggests that iNKT cell–derived APRIL assumes a measurable role in maintaining Ab titers following iNKT activation with α-GC. This was not surprising as the BCMA receptor binds APRIL with a higher affinity than it binds BAFF, indicating that the APRIL/BCMA axis is favored over the BAFF/BCMA axis (19). Additionally, APRIL but not BAFF can bind proteoglycans such as syndecans expressed on PCs (32), resulting in increased interaction of APRIL with PCs.

It is possible that the relative contribution of iNKT cell–derived or –regulated BAFF and APRIL may depend on the immunizing Ag and the specific α-GC adjuvant being used. There are at least 100 variants on the α-GC structure, with some chemically synthesized and others derived from pathogenic bacteria (2). It is possible that during natural infection, the relative production of BAFF and APRIL by iNKT cells is determined by the CD1d/glycolipid presented, as well as the avidity and affinity of TCR interaction, which may influence the outcome of TCR signaling.

Possible limitations imposed by the experimental system were considered. Engraftment of irradiated recipient mice with a 50/50 mix of two different BM types had a built-in assumption that the two donor cell types would engraft and expand equally. This was difficult to test directly because both donor sources were CD45.2-expressing and because BAFF−/− or APRIL−/− donors on a CD45.1 background were not available. However, we observed previously that reconstitution of irradiated CD45.2 mice with a 50/50 mix of Jα18−/− BM and B6 (CD45.1-expressing) BM led to engraftment such that ~65% of the reconstituted cells were presented by Jα18−/−–derived cells (14, 27). The engraftment ratio was highly consistent across several individual mice. Arguably, disruption to the hematopoietic compartment–derived BAFF or APRIL is minimal because fewer non–iNKT cells were BAFF−/− or APRIL−/− than predicted. Furthermore, the intact and sustained Ab responses in the Ag/Alum-immunized mixed chimeras provided evidence against a global deficiency of BAFF or APRIL. Attempts were made to engraft with an 80/20 mixture of BM donor cells, but iNKT cells failed to reconstitute (data not shown).

We were able to discern that activation of splenic and BM iNKT cells led to increased BAFF expression, and that splenic cells, but not BM iNKT cells, could express BAFF directly. Importantly, constitutive expression of BAFF correlated with NKT cell numbers (by comparing Jα18−/− to B6 to Vα14), thus
demonstrating the potential for iNKT cells to regulate the production of survival signals by other cell types.

Our data raise the question of how, when, and where Ag-specific PCs are exposed to iNKT cell–derived BAFF and APRIL, and why it should matter, given that BAFF from the BM stroma can adequately support PCs in the absence of hematopoietic BAFF (29). Because splenic iNKT cells can secrete BAFF directly, then perhaps they provide survival signals to Ag-experienced B cells or plasmablasts before migration to the BM or further differentiation into LLPCs (31). This idea is supported by reports that iNKT cells can interact directly with CD1d+ B cells (33, 34), and that BAFF and APRIL can act in an autocrine manner (35). Furthermore, as spleen has limited niches for PC survival (36), local iNKT cells may provide survival signals to PCs, thereby contributing to sustained Ab titers.

Because we did not detect BAFF expression by BM iNKT cells, this suggests that PC survival is largely governed by stromal cell– or myeloid cell–derived BAFF. However, the total amount of BAFF produced by BM cultures correlated with the number of iNKT cells, suggesting that they could help to coordinate BAFF and APRIL expression by other cell types.

Different tissue microenvironments support the existence of different functional subsets of NKT cells (37). iNKT cells in the spleen and the BM could therefore represent different functional subsets. It is also possible that BAFF-secreting iNKT cells could circulate to and from the BM, providing opportunities for direct interaction with PCs.

Our studies have revealed a new aspect of iNKT cell function and of the role of BAFF and APRIL in vaccination-induced humoral immunity. Determining how, when, and where iNKT cell–derived (and regulated) BAFF and APRIL influence PCs is an active focus of our current investigations that may illuminate possible mechanisms of action in patients with abnormal humoral immune responses.

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Disclosures

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References


