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B Cell Depletion Curtails CD4+ T Cell Memory and Reduces Protection against Disseminating Virus Infection

Ichiro Misumi* and Jason K. Whitmire*†

Dynamic interactions between CD4+ T cells and B cells are needed for humoral immunity and CD4+ T cell memory. It is not known whether B cells are needed early on to induce the formation of memory precursor cells or are needed later to sustain memory cells. In this study, primary and memory CD4+ T cells responses were followed in wild-type mice that were depleted of B cells. Their frequency correlates with vaccine-induced protection in people: individuals with deficiencies in CD4+ T cell memory are not protected well by vaccines, are susceptible to opportunistic infections, and have recurring reactivation of latent virus infections. Ag-specific CD4+ T cells promote vigorous humoral and cellular responses that protect against pathogens, including recall CTL responses that are protective against reinfection (11–14) and act during the memory phase to maintain and/or improve CD8 memory (15). Virus-specific CD4+ T cell interactions actively sustain CD8 responses during persistent virus infection (16–21) in part by producing IL-21 (22–24). Memory CD4+ T cells can directly suppress infection because of their rapid production of IFN-γ (25), directly kill MHC class II target cells (26), and enhance innate responses (27). Our previous analyses showed that B cell–deficient μMT−/− mice are unable to resolve disseminating virus infections because of defects in cellular immunity (9).

B cells contribute to T cell responses in ways that are independent of Ab production (9, 28, 29). B cells express MHC class II costimulatory molecules, lymphotixin, TNF, and OX40L and other cytokines, to interact with and activate Ag-specific CD4+ T cells, influencing their differentiation into effector cells or memory (30–41). B cells stimulate memory CD4+ T cell differentiation and promote follicular helper T cell (Th9) cell differentiation in infection and vaccination models (42–50). In other circumstances, unique regulatory signals may be communicated by B cells to T cells postinfection (p.i.) or vaccination (51–53). B cells also contribute to lymphoid organogenesis, and mice that are congenitally deficient in B cells show profound defects in spleen organization and cellularity that may affect T cell responses. During development, B cells produce lymphotoxin and TNF to differentiate B cell and T cell zones that draw emigrants from the thymus. In this capacity, B cells are involved in normal T cell–B cell segregation and microstructure of the spleen and populating the spleen with other cell types (follicular dendritic cells, fibroblastic reticular endothelial cells, marginal zone populations, dendritic cells). Thus, congenital absence of B cells reduces the frequency of other cell types, including dendritic cells and phagocytic macrophage populations (54) that produce sustained IFN responses (55), and the number of mature naïve T cells that are available in this organ to mount adaptive T cell responses. Finally, B cells can directly limit virus infection, for example, by expressing lymphotoxin-β to stimulate marginal zone macrophage type I IFN.

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expression to limit the spread of vesicular stomatitis virus into neurons (56, 57).

It is not known whether B cells program early memory cell precursors, affect the establishment of memory levels, or act during the maintenance phase to regulate memory CD4+ cell number. Moreover, it is unknown whether the effect of B cells on CD4+ T cell memory is mediated by direct B cell interaction, B cell cytokine production, or B cell–dependent lymphoid organ structure. In this study, we sought to better understand the role of B cells at different stages of the T cell response after acute virus infection by transiently depleting B cells early on or during established memory in immune mice. Using this approach, the effect of B cells on CD4+ T cell memory and immune protection could be disentangled from the effects of B cells on lymphoid architecture. We found that the depletion of B cells during the expansion and contraction phases reduced the number of memory cell precursors and the number and function of memory CD4+ T cells, but these effects were not as severe as observed in μMT−/− mice. B cell depletion in immune mice resulted in no apparent loss of CD4 memory cells, indicating that established memory CD4+ T cell populations are not linked to B cells. Finally, we show that B cell depletion had a profound detrimental effect on the immune response to persisting virus infection, highlighting the key role of B cells in sustaining T cell responses against disseminating virus infection.

Materials and Methods

Mice and virus

We used C57BL/6 mice, SMARTA TCR-transgenic mice specific for the I-Aβ LCMV epitope GP35–40 (58), and μMT−/− (B cell–deficient) mice (59). Adult mice (8–10 wk old) were infected by i.p. administration of 2 × 105 plaque-forming units (PFU) LCMV (Armstrong strain). Some mice were given an intravenous injection of 2 × 106 PFU LCMV-Armstrong, LCMV-t1b, or LCMV-A22 for rechallenge experiments. All mouse experiments were approved by the University of North Carolina Hill Institutional Animal Care and Use Committee. Viral stocks of plaque-purified LCMV were prepared from infected BHK-21 monolayers.

Anti-CD20 mAbs

We received anti-CD20 mAbs (aCD20; clone SD2) from Genentech. Mice were given one or two doses of anti-CD20 (200 μg/mouse in 100 μl volume i.p.) or the same amount of isotype control Ab (IgG2a, anti-keyhole limpet hemocyanin) diluted in PBS.

Flow cytometry

Single-cell suspensions of splenocytes were surface stained with combinations of fluorocein labeled mAbs that were specific for CD4 (clone RM4-5), CD8 (53-6.7), CD19 (6D5), B220 (RA3-6B2), CD11a (M17/4), KLRC1 (2F1/KLRC1), CD127 (A7R34), Thy1.1 (HS51), CCR7 (4B12), ICOS (7E.17G9), CD20 (A12B12), MHC class II (M5/114/15/2), F4/80 (BM8), and Ly6c (HK1.4). CXCR5 was detected through a three-step staining protocol (45) using purified rat anti-CXCR5 (clone2G8), biotin anti-rat IgG (polyclonal sera), then streptavidin-allophycocyanin (Invitrogen). Monomers or streptavidin-APC–conjugated tetramers (DbGP33–41 and I-AbGP 67) were provided by the National Institutes of Health Tetramer Core Facility at Emory University. The intracellular staining (ICCS) assay was performed by culturing splenocytes with or without LCMV peptide in the presence of brefeldin A. After 5 h of incubation, cells were stained for surface markers, washed, fixed with formaldehyde, and then permeabilized and exposed to mAbs specific for IFN-γ (XMG1.2), IL-2 (JES6-5H4), T-bet (4B10), and IL-2 (Fig. 1B and data not shown). Interestingly, the amount of IFN-γ and IL-2 made per cell, as revealed by geometric mean fluorescence intensity of cytokine staining, was greater for SMARTA CD4+ T cells in the μMT−/− mice than in the WT mice (Supplemental Fig. 1B). Thus, the expansion of SMARTA CD4+ T cells is largely normal, but the cytokine output of SMARTA CD4+ T cells is increased when the cells differentiate in the absence of B cells.

The T cell response was examined at day 44, which is during the memory phase. The memory SMARTA CD4+ T cells represented ~0.3% of splenocytes in the WT mice; however, SMARTA CD4+ T cells were near the limits of detection in the μMT−/− mice (Fig. 1C). These frequencies corresponded to ~300 memory SMARTA CD4+ T cells in WT mice and ~300 memory SMARTA CD4+ T cells in the μMT−/− mice (Fig. 1D). Thus, there was a 220-fold reduction in memory in the μMT−/− mice. The defect was specific for CD4+ T cells, because the memory CD8+ T cell response in the μMT−/− mice appeared normal (data not shown) (9, 61). These data indicate that the loss of CD4 memory in immune μMT−/− mice is due to the physical absence of memory cells rather than the persistence of functionally impaired CD4 memory cells.

The earlier data show that the same cells undergo different fates depending on the recipient mouse. Memory cell differentiation begins early on with a subset of effector cells (memory precursor cells) transiting into the memory pool (62). The loss of CD4 memory in the B cell–deficient mice could represent a defect in the formation of memory precursor cells among the effector cells,
In this experimental setup, the early differentiation steps of CD4+ T cells were performed in the presence or absence of B cells, but the subsequent survival of the CD4+ T cells could be compared in the same host. After another 32 d, which is sufficient for the donor cells to transit to memory, the mice were either left unchallenged to evaluate the establishment/maintenance of memory cells under homeostatic conditions or challenged with high-dose LCMV-Armstrong to evaluate the recall response of the donor memory cells. The effector CD4+ T cells from the μMT−/− mice and WT mice established comparable levels of memory when transferred into WT mice (Fig. 2B, left, white bars). Thus, the effector CD4+ T cells generated in μMT−/− mice are capable of forming memory cells. These quiescent memory cells were also functional, because they were responsive to the rechallenge infection and underwent expansion (Fig. 2B, left, shaded bars).

The two populations of effector SMARTA CD4+ T cells were also transferred to μMT−/− mice. However, the abundance of the memory SMARTA CD4+ T cells was greatly reduced in the μMT−/− mice compared with the WT recipients (Fig. 2B, right, white bars), indicating that both donor cells poorly transitioned to memory in these hosts. Neither donor cell population responded vigorously upon rechallenge (Fig. 2B, right, shaded bars). These data show that CD4 memory precursors can form without B cells; however, μMT−/− mice fail to sustain these cells into memory.

**Sustained depletion of B cells by anti-CD20 mAb**

The earlier data show that despite the early induction of CD4+ T cells that are capable of becoming memory cells, the long-term survival of CD4 memory was defective in μMT−/− mice because of the physical loss of memory cells. There are several possible explanations for the defect in memory in the μMT−/− mice. The μMT−/− mice have a disorganized spleen structure (63), so there may be a deficiency in stomal cell numbers resulting in low basal homeostatic cytokines, such as IL-7, that are needed to sustain memory CD4+ T cells. Alternatively, the μMT−/− mice have defects in critical B cell–derived cytokines that affect CD4+ T cell survival. To better understand the role of B cells at different stages of CD4 memory formation, we analyzed T cell responses in WT mice that have normal stromal cell organization but were depleted of B cells by monoclonal anti-CD20 Ab at different times p.i.

CD20 is expressed on immature B cells, mature B cells, and a subset of memory B cells, but not pro-B cells, plasmablasts, or plasma cells (3, 64). The expression of CD20 has been reported for unchallenged mice (40, 64), but the expression pattern of molecules can change dramatically in the context of infection because of the inflammatory environment. We found that CD20 in the spleen was confined to B cell populations and not induced on T cells, macrophages, or DC subsets p.i. (data not shown). We next evaluated the effect of anti-CD20 treatment on B cell frequencies in uninfected mice or in mice that were given LCMV-Armstrong. The depleting mAb against CD20 acts by inducing either FcyR-dependent (Ab-dependent cell–mediated cytotoxicity) or complement-mediated lysis of target cells (4, 65). In uninfected mice, B cells were effectively depleted by anti-CD20, as CD19+ B220+ B cell populations were reduced from 45 to 0.5% in the spleen and the depletion was maintained for 45 d (Fig. 3A). A similar loss of CD20+ B cells was also observed (data not shown). A kinetic analysis of B cell depletion in uninfected mice revealed that the vast majority of B cells (>98%) were eliminated within 1 wk after anti-CD20 was given, and the depletion lasted 40 d (Fig. 3B). After day 45, the frequency of B cells began to increase until normal frequencies were observed by day 60. A similar analysis of anti-CD20–treated mice that were subsequently given LCMV-Armstrong showed that there was a 2-log decrease in B cell numbers within 1 wk and the B cells remained low in number for 40 d (Fig. 3C). The anti-CD20 resulted in serum levels of anti-LCMV Ab that were at or below detection at day 40 (Fig. 3D). Thus, anti-CD20 treatment is specific, long-lasting with a half-life of nearly 1 mo, and is unaffected by the inflammation associated with live infection.

Previously, it was shown that μMT−/− mice and other mice with disrupted splenic organization have deficient type-1 IFN responses (54). B cells maintain a subcapsular sinus population of macrophages that are responsive to vesicular stomatitis virus infection and make protective amounts of type-1 IFN (56, 57). The early IFN production during LCMV infection is from plasmacytoid dendritic cells and then macrophage populations (54, 55). Therefore, we examined the B cell–depleted mice for serum levels of IFN and found that they were partially reduced in the anti-CD20–depleted mice, but not to the extent observed in μMT−/− mice (Fig. 3E). These results show that even when lymphoid organo-

**FIGURE 1.** Absence of virus-specific CD4+ T cell memory in μMT−/− mice. WT (B6) and B cell–deficient (μMT−/−) mice were given 2 × 10⁴ SMARTA/Ly5a CD4+ T cells and then infected with LCMV-Armstrong a few days after engraftment. The T cell response was analyzed at day 8 (A, B) or 44 (C, D) p.i. by flow cytometry. (A) At day 8 p.i., spleen cells were harvested and costained for CD4, Ly5a to identify the SMARTA CD4+ T cells. The dot plots show examples of surface-stained splenocytes with the SMARTA cells identified within the ovals. The numbers represent their percentage among all spleen cells. (B) ICCS was used to quantify T cell reactivity to LCMV-GP61–80 peptide. The dot plots are gated on CD4+ T cells and show donor cell (Ly5a+ expressing IFN-γ). The numbers represent the percentage of CD4+ T cells in each quadrant. (C) The dot plots show surface staining for CD4 and Ly5a at day 45, with the SMARTA CD4+ T cells identified within the ovals. (D) The bar graph shows the total number of splenic SMARTA CD4+ T cells in the two groups of mice. The number above the white bar indicates the ratio of memory SMARTA cells in WT mice to the number in B cell–deficient (BCKO) mice. Data represent two mice per group from a representative experiment.
CD4+ T cells were engrafted into these mice so that we could follow the same population of cells in the different hosts without the concern of B cell effects on stromal architecture. The engraftment of the naive SMARTA CD4+ T cells was not affected by the depletion of B cells when there was no infection (data not shown). The mice were then infected with LCMV-Armstrong, and the viral load and virus-specific T cell and B cell responses were quantified at 8 d p.i. This treatment regimen led to a significant loss of B cells at day 7 and then infected with LCMV. At the indicated times p.i., serum was collected and analyzed for IFN-γ levels by ELISA. (B and C) Data represent 2–3 experiments with 3 (day 0 p.i.), 11–13 (day 40 p.i.), and 11–13 (days 70–90 p.i.) mice/group. (D) Data represent two experiments with two to six mice per group at each time point.

A two-tailed Student t test was used to evaluate significance: **p < 0.01, ***p < 0.001.

### FIGURE 2

B cells are required during the contraction phase to produce functional memory CD4+ T cells. CD4+ T cells were allowed to differentiate into effector cells and memory precursor cells in either B cell–sufficient or B cell–deficient (BCKO) mice. The cells were harvested and their relative survival into the memory phase was compared in the same hosts. (A) An illustration of the experimental setup. A set of B6 and μMT−/− mice were given 2 × 10^5 SMARTA (Thy1.1+) CD4 T cells 2 d before the primary infection with LCMV-Armstrong. In parallel, sets of other infection-matched B6 and μMT−/− mice were generated. At 8 d p.i., 5 × 10^5 SMARTA CD4 T cells from each donor mouse were cotransferred into the infection-matched B6 or BCKO recipients. Thirty-two days after the cotransfer (40 d after the primary infection), the recipients were rechallenged with LCMV-Armstrong (2 × 10^6 PFU i.v.) or left unchallenged. Six days later, splenocytes were isolated and surface stained for CD4, Thy1.1, and Ly5a to identify the two donor cell populations. (B) The left graph shows the number of memory Thy1.1+ SMARTA CD4+ T cells (generated in WT mice) or Ly5a+ SMARTA CD4+ T cells (generated in μMT−/− mice) in the unchallenged B6 recipients (open bars) or in the challenged B6 recipients (shaded). The right graph shows the number of memory SMARTA CD4+ T cells in the unchallenged (open bars) or challenged (shaded) B cell–deficient recipients. The numbers above the bars indicate the fold expansion of the memory cells upon challenge. Data are pooled from two independent experiments with six to seven recipient mice per group.

### FIGURE 3

Anti-CD20 treatment leads to durable loss of B cells followed by cell recovery. Uninfected or infected mice were given 200 μg anti-CD20 or isotype control (anti-keyhole limpet hemocyanin IgG2a mAb) into the peritoneal cavity to evaluate the effectiveness and longevity of the B cell depletion. (A) The dot plot shows an example of splenocytes surface stained for B cell markers (B220 and CD19) 28 d after anti-CD20 was given. (B) The line graph shows the number of CD19+B220+ cells per spleen as measured by flow cytometry at days 0, 7, 28, 40, 49, and 75 posttreatment in uninfected mice. Data represent two experiments with three to six mice per group at each time point. (C) B6 mice were treated with mouse anti-CD20 or isotype control at 14 and 7 d preinfection. The line graph shows the number of B220+CD19+ cells in the spleen at the indicated days p.i. (D) Mice were depleted of B cells by two injections of anti-CD20 at days −14 and −7 preinfection. At the indicated times p.i., sera were collected and the amount of LCMV-specific IgG was quantified by ELISA. (E) Mice were depleted of B cells at day 7 and then infected with LCMV. At the indicated times p.i., serum was collected and analyzed for IFN-γ levels by ELISA. (B and C) Data represent 2–3 experiments with 3 (day 0 p.i.), 11–13 (day 40 p.i.), and 11–13 (days 70–90 p.i.) mice/group. (D) Data represent two experiments with two to six mice per group at each time point.

A two-tailed Student t test was used to evaluate significance: **p < 0.01, ***p < 0.001.

### VIGOROUS PRIMARY T CELL RESPONSE BUT REDUCED CD4+ T MEMORY TO ACUTE LCMV INFECTION IN THE ABSENCE OF B CELLS

The data in Fig. 2 indicate that B cells are required after day 7, during the contraction or memory phases, to sustain CD4 memory. To better understand when B cells are needed, we treated cohorts of WT mice with anti-CD20 or isotype control Ab at days −14 and −7 to remove B cells (Fig. 4A). LCMV-specific Thy1.1+ SMARTA CD4+ T cells were engrafted into these mice so that we could follow the same population of cells in the different hosts without the concern of B cell effects on stromal architecture. The engraftment of the naive SMARTA CD4+ T cells was not affected by the depletion of B cells when there was no infection (data not shown). The mice were then infected with LCMV-Armstrong, and the viral load and virus-specific T cell and B cell responses were quantified at 8 d p.i. This treatment regimen led to a significant loss of B cells at day 8 (Fig. 4B), and the mice controlled the infection in the liver, lung, and kidney at this time (data not shown). Consistent with our earlier analyses of endogenous CD4+ T cells, control-treated WT mice, B cell–depleted mice, and μMT−/− mice generated elevated frequencies of SMARTA CD4+ T cells (Fig. 4C), representing ≥1000-fold expansion of cells in all groups. However, there was a significant ∼2-fold lower number of SMARTA CD4+ T cells in the B cell–depleted mice compared with B cell–sufficient
mice, as observed previously for μMT−/− mice (9). The proportion of SMARTA CD4+ T cells expressing IFN-γ, IL-2, and TNF was unaffected by B cell depletion or marginally increased (Fig. 4D, Supplemental Fig. 1A, 1B, and data not shown), indicating that effector differentiation was not inhibited by the absence of B cells. Primary virus-specific CD8+ T cell numbers were unaffected by the loss of B cells (Fig. 4E), as observed previously for μMT−/− mice.

After the peak response, T cells undergo contraction in number and establish a pool of memory cells. We assessed whether the early depletion of B cells would impact T cell memory. At day 40 p.i., the B cell–depleted mice continued to show a 1000-fold reduction in B cell number compared with isotype-treated mice (Fig. 4F). The immune control–treated mice contained ∼15 × 10^4 memory SMARTA CD4+ T cells. However, there was a reduction in this number to ∼5 × 10^4 memory CD4+ T cells in the B cell–depleted mice (Fig. 4G), indicating that approximately two thirds of CD4 memory requires B cells, even when lymphoid organogenesis is normal. The number of memory CD4+ T cells in μMT−/− mice was reduced ∼1000-fold compared with the immune control mice, consistent with our earlier findings concerning endogenous CD4+ T cell responses and the data in Fig. 1 (9). The memory SMARTA CD4+ T cells in B cell–depleted mice showed significant reductions in the percentage of cells that expressed IFN-γ, IFN-γ with

FIGURE 4. Early B cell depletion transiently reduces CD4 memory, but not CD8 memory. (A) An illustration of the experimental approach to assess the effect of early B cell depletion on a defined population of virus-specific CD4+ T cells. B6 mice were treated with mouse anti-CD20 mAbs to deplete B cells or isotype control Ab at days −14 and −7 preinfection. The Ab-treated mice or μMT−/− mice were engrafted with 2 × 10^4 SMARTA/Thy1.1+ CD4+ T cells at day −3 and then given LCMV-Armstrong. Spleen cells were analyzed for the presence of B cells and virus-specific T cells at the indicated times p.i.: day 9 (B–E), day 40 (F–I), day 70 (J–M). (B, F, and J) The number of B220+CD19+ B cells per spleen in mice given anti-CD20 (+) or isotype Ab (−). (C, G, and K) Total number of SMARTA cells per spleen in mice given anti-CD20, or isotype control, or in μMT−/− (BCKO) mice. (D, H, and L) The percentage of SMARTA CD4+ T cells that were double positive for IFN-γ and IL-2 in an ICCS assay. (E, I, and M) The number of CD8+ T cells specific for GP33–41 based on ICCS. The data represent three experiments with 6–13 mice/group. A two-tailed Student t test was used to evaluate significance with *p < 0.05, **p < 0.01, ***p < 0.001.
IL-2, or IFN-γ with TNF compared with cells in control immune mice (Fig. 4H, data not shown). In contrast with CD4 memory cells, there was no loss in the number of cytokine +ve CD8+ memory T cells (Fig. 4I), consistent with earlier analyses (9). Thus, B cells are required for most of the memory CD4+ T cell pool and improve the capacity of memory CD4+ T cells to make cytokine. The greater loss of CD4+ T cell memory in μMT−/− mice suggests that lymphoid architecture plays a major role in the maintenance of CD4+ T cell memory, but not CD8+ T cell memory.

In this same cohort of mice, B cells returned to normal abundance by day 70 (Fig. 4J). At this time, memory SMARTA CD4+ T cells returned to normal number in the mice that had been depleted of B cells, but not the μMT−/− mice (Fig. 4K). Despite the recovery in B cell number and the increase in SMARTA cell abundance, memory SMARTA CD4+ T cells continued to show deficits in cytokine output. For example, the percentage of SMARTA CD4+ cells that expressed IFN-γ with IL-2 remained lower than that observed in isotype-treated immune mice (Fig. 4L). The per-cell amount of IFN-γ was reduced; although there was no significant difference in IL-2 or TNF output between the two groups of mice (Supplemental Fig. 1C, data not shown). By comparison, the few detectable SMARTA CD4+ T cells present in the μMT−/− mice showed highly significant reductions in their ability to produce multiple cytokines, and there were major reductions in cytokine output per cell (Fig. 4L, Supplemental Fig. 1C). These data suggest that memory CD4+ T cells accumulate deficiencies in cytokine production across time when there are no B cells. The recovery in memory CD4+ T cell frequency that is associated with increases in B cell number does not rescue memory CD4+ T cell defects in cytokine production.

Throughout these times p.i., virus-specific CD8+ T cells remained at elevated frequencies without B cells (Fig. 4E, 4I, 4M), and the recovery of B cells did not result in more memory CD8+ T cells, underscoring the independence of B cells and CD8+ T cell number. However, there were functional and phenotypic changes in that compartment that emerged during the memory phase. There were no apparent alterations in cytokine output early on (Supplemental Fig. 2A–C), but by day 40 there were reductions in the percentage of IFN-γ+IL-2+ double-positive CD8+ T cells in B cell–depleted mice and in μMT−/− mice, and lower amounts of cytokine made by the memory CD8+ T cells in these mice (Supplemental Fig. 2D, 2E). These reductions in cytokine production continued to day 70, when B cell numbers recovered in the B cell–depleted mice (Supplemental Fig. 2F, 2G). During the memory phase, the CD8+ CD11ahi population that contains all of the virus-specific memory CD8+ T cells (66, 67) was evenly distributed between CD8+ T cells with the short-lived effector cell phenotype and those with the characteristic markers of long-lived memory cells (68) that express IL-7R (Supplemental Fig. 2H, open bars). In contrast, the majority of memory phenotype CD8+ T cells in the B cell–deficient mice were short-lived effector cells (Supplemental Fig. 2H, shaded bars). Thus, stable pools of memory CD8+ T cells form in B cell–depleted mice as observed for μMT−/− mice (9, 61, 69–71), but the T cells appear activated and show reductions in cytokine production.

**B cell depletion does not diminish established T cell memory**

The earlier analyses involve mice that were depleted of B cells preinfection, but the duration of B cell loss continues through the contraction and memory phases of CD4+ T cells (Fig. 3). To better understand whether B cells function early on or during the contraction phase or memory maintenance phases, we explored the effect of staggering the B cell depletion to later times p.i. A cohort of mice containing SMARTA cells was given acute LCMV. At day 7, the mice were depleted of B cells or not, and the number and function of memory cells was examined on day 21 (Fig. 5A). At day 21, the control-treated mice had 2 × 10^7 B cells (Fig. 5B) and 6 × 10^6 memory SMARTA cells (Fig. 5C). In contrast, B cell–depleted mice had ~10^7 B cells and a 2.4-fold reduction of memory CD4+ T cells (Fig. 5B, 5C), and these cells were less able to make IFN-γ (Fig. 5D). By day 70, the number of B cells and memory CD4+ T cells was equivalent to the undepleted mice (data not shown). Thus, B cell depletion initiated during the contraction phase exaggerates the loss of early memory cells, but the effect is reversed when B cells recover in number.

Another cohort of mice were immunized and allowed to establish T cell memory. During the memory phase (day 40 p.i.), some of the immune mice were given isotype-control Ab or anti-CD20 to

**FIGURE 5.** B cell depletion during contraction reduces CD4 memory, but pre-existing CD4 memory is unaffected by B cell loss. (A–D) Mice engrafted with 2 × 10^5 SMARTA CD4+ T cells were infected with LCMV-Armstrong. T cells were allowed to differentiate normally until day 7, when the mice were given anti-CD20 (+) to deplete B cells through the contraction phase or treated with isotype control (−). Splenocytes were analyzed at day 21. (B) The number of B cells per spleen based on B220 and CD19 costaining. (C) The number of SMARTA cells per spleen. (D) The percentage of SMARTA CD4+ T cells that made IFN-γ and IL-2 in an ICCS assay. (E–H) Naive mice with 2 × 10^7 naive SMARTA CD4+ T cells were given LCMV-Armstrong infection and allowed to develop memory. At day 40, some of these immune mice were given anti-CD20 (+) or isotype-control Ab to evaluate the effect of B cell loss on existing memory cells. The mice were analyzed 14 d after Ab treatment. (F) The number of B cells at day 54. (G) The number of memory SMARTA CD4+ T cells per spleen. (H) The percentage of SMARTA CD4+ T cells that made IFN-γ with IL-2 in an ICCS assay. (B–D) Data represent seven to eight mice per group from one of two experiments. (F–H) Data represent the average of four mice per group from one of two similar experiments. A two-tailed Student t test was used to evaluate significance: *p < 0.05, **p < 0.01, ***p < 0.001.
deplete B cells (Fig. 5E). Two weeks later (day 54), the number of B cells and memory T cells was quantified. There was a 200-fold reduction in B cells in the spleen (Fig. 5F), although there remained \(\sim 10^5\) B cells, some of which are likely memory B cells, plasmablasts, or germinal center B cells (64, 72, 73). The numbers of memory SMARTA CD4+ T cells and CD8+ T cells were unaffected by this reduction in B cells (Fig. 5G and data not shown), although there was a modest reduction in the percentage of SMARTA CD4+ T cells that could make IFN-\(\gamma\) (Fig. 5H). Another set of immune mice that were allowed to recover B cells and were analyzed at day 210 p.i. also showed no apparent change in the number or cytokine production of memory T cells compared with those in mice that had B cells the entire time. Thus, B cell depletion does not cause major changes in T cell memory once it is established.

Early B cell depletion reduces memory precursor populations

Thus far, the data show that early B cell depletion before infection or during the contraction phase reduces the formation of CD4 memory (Figs. 4, 5). We next examined whether this is due to a defect in the formation of memory precursor cells. Th1 and TFH-like CD4+ T cells can form early p.i. and represent distinct lineages that develop memory (43–47). Among the virus-specific CD4+ T cells at day 8, memory precursors are found that re-express IL-7R and are Ly6C\(^\text{lo}\) and T-bet+ (62). In the infected isotype-control–treated mice, \(\sim 37\%\) of SMARTA CD4+ T cells were Ly6C\(^{\text{lo}}\)T-bet+ (Fig. 6A, 6B). By comparison, there was a statistically significant decrease in the proportion of T cells that were Ly6C\(^{\text{lo}}\)T-bet+ in B cell–depleted mice and a greater decrease in the \(\mu\text{MT}^{+/−}\) mice (Fig. 6A, 6B). Thus, the lower level of memory in the B cell–depleted mice is associated with a reduction in early effector cells with memory potential.

Among the memory precursors within the effector cell population, a subset expresses the “central memory” phenotypic marker, CCR7, which maintains CD4+ T cells in T cell zones and is associated with improved homeostatic survival across time (48, 62). About a quarter of effector SMARTA CD4+ T cells expressed CCR7 in WT mice and in B cell–depleted mice (Fig. 6C), but this population was greatly reduced in the \(\mu\text{MT}^{+/−}\) mice. These data suggest that memory precursors form at reduced levels without B cells, but these cells are capable of undergoing homeostatic cell division to recover their number when placed in mice with B cells (Fig. 2) or when B cells return in B cell–depleted mice (Fig. 4).

A number of studies have shown a direct relationship between B cells and the formation of TFH CD4+ T cells (43–48). Consistent with those studies, far fewer TFH developed in \(\mu\text{MT}^{+/−}\) mice than B cell–sufficient mice (Fig. 6D, 6E). By comparison, B cell–depleted mice showed a significant reduction in the number of CXCR5+ICOS+ CD4+ T cells compared with B cell–sufficient mice, yet there were significantly more TFH in the B cell–depleted mice than in the \(\mu\text{MT}^{+/−}\) mice (Fig. 6D, 6E). Thus, approximately one third of the TFH response can occur without B cells when stromal architecture is preserved.

B cell depletion impairs T cell responses to disseminating virus infection and results in exaggerated weight loss

\(\mu\text{MT}^{+/−}\) mice are highly susceptible to disseminating virus infections (9, 74–76). When confronted with LCMV-Clone13, LCMV-tib, or LCMV-A22 strains, \(\mu\text{MT}^{+/−}\) mice lose virus-specific CD4+ T cell responses, as well as CD8+ T cell responses, partly through exaggerated T cell loss and through functional T cell exhaustion. The earlier data (Fig. 4) for acute infection show that early B cell depletion results in an intermediate phenotype where CD8+ T cells are largely unaffected numerically and CD4 memory is transiently reduced until B cells recover in number. We next asked whether these effects would impair immunity to a more aggressive infection.

It is well established that CD4+ T cells are required to sustain CD8+ T cell responses during infections with disseminating strains of LCMV (17, 19, 22, 23, 77–80). Without T help, virus-specific CD8+ T cells undergo deletion or functional exhaustion. We sought to learn whether B cell depletion affects the ability of mice to eliminate disseminating LCMV infection. Groups of mice were depleted of B cells or given isotype-control Ab and then exposed to LCMV-11b. All mice showed similar amounts of weight loss during the first week p.i. (Fig. 7A). However, the B cell–sufficient mice recovered weight over the next week. In contrast, \(\mu\text{MT}^{+/−}\) mice showed greater weight loss that was sustained until day 21. The B cell–depleted mice demonstrated even more weight loss than the infected \(\mu\text{MT}^{+/−}\) mice with no evidence of recovery (Fig. 7A).
The viral load and antiviral T cell responses were evaluated at day 21 p.i. The B cell-sufficient mice controlled replicating LCMV-11b in the serum, liver, and lung, and had reduced levels of virus in the kidneys at day 21 (Fig. 7B). In contrast, B cell-depleted mice and μMT−/− mice showed several logs increase in viral titers in each of these compartments (Fig. 7B). The inability of B cell–deficient mice to resolve this disseminating infection correlated with poor T cell responses. Tetramer +ve (DbGP33–41) CD8+ T cells were present in all three groups, but there was a >10-fold reduction in tetramer+ CD8+ T cells in B cell–depleted mice compared with B cell–sufficient mice (Fig. 7C, 7D, top panels). Compared with the B cell–sufficient mice, there was an ~50-fold reduction in the number of CD8+ T cells capable of making IFN-γ in the B cell–deficient mice (Fig. 7C, 7D, bottom panels). Tetramer +ve (I-AbGP 67) CD4+ T cells and IFN-γ–competent CD4+ T cells were reduced 10- to 20-fold in the B cell–depleted mice (Fig. 7E, 7F). Thus, B cell depletion severely decreases CD4+ and CD8+ T cell responses through a combination of reduced T cell number and induction of functional exhaustion, preventing virus control and increasing pathogenesis.

Discussion

Several drugs that deplete B cells are given to treat people with autoimmune disorders. These therapies are highly tolerated and adverse problems are relatively rare. However, there is evidence that some individuals experience recurrent infections that depend on cellular immunity (1, 2). To better understand the role of B cells in the formation of T cell responses, we compared antiviral T cell responses in B cell–depleted mice, μMT−/− mice, and B cell–sufficient mice. We show that early T cell differentiation unfolds normally in μMT−/− mice, but these mice fail to support CD4+ T cell memory. However, effector T cells that form in the absence of B cells are capable of surviving on into memory when transferred to B cell–sufficient mice. We evaluated the role of B cells in mice that are not congenitally deficient in B cells but were depleted early on or during the memory phase of the T cell response after virus infection. We confirmed that B cells are not needed to generate primary T cell responses or eliminate acute virus infection. However, eliminating B cells before infection or during the contraction phase reduced memory CD4+ T cell number and cytokine production, although not to the extent observed in mice that are congenitally deficient in B cells. Once T cell memory was established, B cell depletion had minimal effect on CD4 or CD8 memory. There appears to be a direct linkage between the frequency of B cells and CD4+ T cell memory: when B cells recovered from Ab-mediated depletion, memory SMARTA cells also increased numerically. We also found that B cells play a key role in sustaining cellular immunity to a disseminating virus infection. Taken together, the data indicate that B cells improve the early establishment and survival of memory T cells post–acute infection and are involved in the vigorous T cell responses that are needed to eliminate aggressive infections. A prediction based on our study is that B cell–depletion therapies in people who are otherwise immunologically intact will leave their pre-existing T cell memory intact, but they will form weaker CD4+ T cell memory to new Ags and will be at risk for systemic infections.

A major limitation with using μMT−/− mice is that their spleens do not form properly, which can potentially impact T cell responses (81). In this study, we circumvented this problem by following T cell responses in mice that generated spleens with proper microarchitecture. One caveat to our analyses is that long-term B cell–depletion mice may eventually disrupt some of the existing microarchitecture. For example, there was a gradual loss of marginal zone cells when B cells were conditionally eliminated by an IFN-inducible Cre/Igsa-floxed mouse model (82). Likewise, CD70-transgenic mice gradually lose B cells and marginal zone structure (82). These long-term changes in lymphoid organization may impact subsequent cellular immune responses to infection. For example, phagocytic populations in the marginal zone contribute to sustained IFN production during active LCMV infection (54, 55), and direct IFN signaling drives T cell differentiation into memory (83–85). We observed a reduction in type 1 IFN in μMT−/− mice, as reported previously (54), and a partial reduction in IFN in the B cell–depleted mice (Fig. 3E). The reduction in IFN may be caused by the loss of a macrophage population or plasmacytoid dendritic cells in the spleen after B cell depletion. Nevertheless, the reduction in type 1 IFN was not so severe to prevent significant induction of T cell responses and memory as observed in type 1 IFN–deficient mice. Moreover, delaying the B cell depletion until after the early inflammatory response (Fig. 5C) showed that B cells increase early CD4 memory.

CD4 memory is reduced when B cells are depleted. We observed that SMARTA CD4+ T cells were CCR7+ in the B cell–depleted mice (Fig. 6C), and memory CD4+ T cells that are CCR7+ are thought to have greater proliferative and self-renewing capacity compared with CCR7− CD4+ T cells (43). In contrast, μMT−/− mice induced CD4+ T cells that were mostly CCR7+ and likely had reduced memory cell potential (43), and the μMT−/− mice fully lose memory cells with time (Fig. 1). The μMT−/− mice and, to a lesser extent, B cell–depleted mice generated CD4+ T cells that were shifted to the effector cell phenotype with enhanced IFN-γ, IL-2, and TNF output (Fig. 4D, Supplemental Fig. 1B), consistent with the formation of cells that are intrinsically shorter lived. In addition, the B cell–sufficient environment appears to stimulate intrinsic changes in SMARTA CD4+ T cells that enable them to undergo a better recall response compared with SMARTA CD4+ T cells in μMT−/− mice (Fig. 2B). Among other potential changes, greater levels of CCR7 expression are associated with improved recall responses (43, 62). Nevertheless, virus-specific CD4+ T cells could be affected by regulatory cells. We do not see reductions in the abundance of Tregs (CD4+CD25+Foxp3+) in the B cell–deficient mice after LCMV infection (data not shown); however, it is plausible that regulatory B cells restrain cytokine output by effector CD4+ T cells, as observed in other models (31, 49, 51, 81).

In addition to influencing the formation of memory cell precursors, B cells contribute to memory during the contraction phase by sustaining virus-specific CD4+ T cells. CD4+ T cell memory could be rescued by isolating the T cells from μMT−/− mice and placing them into B cell–sufficient mice, where they recovered numerically (Fig. 2). This notion is further supported by the finding that B cell depletion initiated during the contraction phase reduced the number of memory CD4+ T cells compared with B cell–sufficient mice (Fig. 5C). Thus, B cells enhance the formation of CD4+ memory precursors and improve their survival during the contraction phase; however, we do not know which cytokine(s) produced by B cells is required for these effects. B cells and sustained antigenic stimulation contribute to the formation of T FH cells (45, 72, 86, 87). T FH differentiation begins with the expression of Bcl6 by day 3 after acute LCMV infection (88). Both T FH and Th1 cells enter the memory pool and respond to re-infection (44, 62, 89–92). However, memory T FH can respond to infection in the absence of B cells and remain CXCR5+ up to day 10 p.i., whereas naive CD4+ T cells fail to efficiently form CXCR5+ cells (44). Thus, established T FH memory cells appear to be less dependent on B cells than primary effector cells. Our findings are consistent with this, because B cell depletion during the expansion or contraction phases reduced CD4 memory, whereas depletion initiated at day 40 (Fig. 5G) had minimal effect on memory. Further studies
FIGURE 7. B cell depletion diminishes immunity to disseminating LCMV-t1b infection. C57BL/6 mice (with or without anti-CD20 treatment 1 wk preinfection) and μMT−/− mice were infected i.v. with 2 × 10⁶ PFU LCMV-t1b. (A) Weight loss during LCMV-t1b infection (mean ± SEM with three to six mice/group/day). (B) The viral burden in the mice was measured at day 21 in the serum or indicated tissues. Dotted line indicates the limit of detection of the plaque assay. (C–F) Spleen cells from infected mice were analyzed on day 21 p.i. by tetramer staining or ICCS. (C) GP₃₃-specific CD8 T cell responses in the spleen were quantitated by tetramer staining (top panel). The dot plots are gated on CD8⁺ cells (top) and show examples of GP₃₃-tetramer⁺ CD44⁺ CD8⁺ T cells. The bottom dot plots are gated on all splenocytes and show CD8 T cell production of IFN-γ as measured by ICCS assay. Numbers indicate the percentage of cells in each region. (D) Bar graphs show the average (± SEM) number of GP₃₃-tetramer⁺ CD44⁺ CD8⁺ T cells (top panel) and IFN-γ-producing, GP₃₃-specific CD8 T cells per spleen in each group of mice. (E) GP₆₁-specific CD4 T cell responses in the spleen were quantitated by tetramer staining (top panel) or ICCS (bottom panel). The upper dot plots are gated on all CD4⁺ T cells and show examples of GP₆₁-tetramer⁺ CD44⁺ CD4⁺ T cells. The bottom plots are gated on all splenocytes and show CD4 T cell production of IFN-γ. The numbers indicate the percentage of cells in each region. (F) The bar graphs show the average (± SEM) number of GP₆₁-tetramer⁺ CD44⁺ CD4⁺ T cells (top panel) and IFN-γ-producing GP₆₁-specific CD4⁺ T cells (bottom panel) per spleen. (B–F) Data represent three to six mice per group. Asterisks indicate statistical significance (*p < 0.05, **p < 0.01, ***p < 0.001) by a two-tailed Student t test.
are needed to determine the temporal requirements of B cells for the establishment and maintenance of Th2 and Th1 memory cells. B cells eventually recover in mice that had been given anti-CD20 Ab (Fig. 4K) and, at this time, memory CD4+ T cells repopulate the spleen. It is plausible that memory CD4+ T cells reside in another niche when B cells are absent but return to the spleen when B cells recover. Alternatively, we speculate that the recovery of memory T cells could be caused by enhanced homoeostatic cell division because of increased lymphopoiesis-associated cytokines. Marginal zone cells express, or trans-present, IL-15 that can act on memory T cells and stimulate their survival (93). Thus, B cell depletion may reduce monocyte populations or stromal cell number to deprive T cells of essential survival/maintenance cytokines, such as IL-7 or IL-15. The return of these sources of homoeostatic cytokines may induce memory T cells to proliferate and accumulate to normal levels.

Chronic virus infections cause significant amounts of morbidity and mortality throughout the world, and many of the immunological and pathological consequences of chronic infection can be modeled in mice that are given variants of LCMV that persist over time. Our data show that B cells improve T cell responses post–acute infection, and these positive effects are somewhat more apparent during chronic virus infection, where robust CD4+ T cell and CD8+ T cell responses need to be sustained to eliminate the infection. The data in Fig. 7 show that B cell depletion impairs immunity to disseminating virus infection, implying that B cells directly or indirectly contribute factors that prevent T cell exhaustion. B cell production of cytokines or Ab may contribute to the resolution of infection (76, 94, 95). Overall, our findings suggest that B cell–depletion therapies of cytokines or Ab may contribute to the resolution of infection (76, 94, 95). Overall, our findings suggest that B cell–depletion therapies of cytokines or Ab may contribute to the resolution of infection (76, 94, 95).

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Disclosures

The authors have no financial conflicts of interest.

References


Supplemental Figure 1. Early B cell depletion reduces cytokine production by memory CD4+ T cells.

Additional analyses were performed using the same mice described in Figure 4 that were depleted of B cells before infection. SMARTA CD4+ T cell responses were evaluated by ICCS at day 9 or day 70 after infection. A group of muMT-/- (BCKO) mice are included for reference. (A) An illustration of the experimental plan. (B) SMARTA CD4+ T cell responses at day 9 post-infection. The graphs show the geometric fluorescence intensity of IFN (left) or IL-2 (right) staining by SMARTA CD4+ T cells. (C) SMARTA CD4+ T cell responses at day 70. The left graph shows the gMFI of IFNγ staining and the right graph shows the gMFI of IL-2 staining for the SMARTAs. Each symbol represents an individual mouse across 2 experiments. A two-tailed Student’s t-test was used to evaluate significance with *P <0.05; **P <0.01; ***P <0.001.
Supplemental Figure 2. B cell depletion before infection reduces cytokine production by CD8 T cells.

The CD8+ T cell response in the mice described in Figure 4 were further characterized. B6 mice were treated with mouse anti-CD20 mAbs to deplete B cells or isotype control antibody at day-14 & day-7 before infection. The antibody-treated mice or MT-/- mice were engrafted with 2x10^4 SMARTA/Thy1.1+ CD4+ T cells at day -3 and then given LCMV-Armstrong. Spleen cells were analyzed for CD8+ T cell cytokine production at the indicated times after infection: day 9 (A-C), day 40 (D-E), and day 70 (F-G).

(A) The dot plots are gated on all splenocytes and show CD8+ T cell expression of IFN in response to GP33 peptide stimulation. (B, D, F) The percentage of CD8+ T cells that co-express IFN with IL-2 in mice given anti-CD20 (+) or isotype antibody (-) or in MT-/- mice (BCKO). (C, E, G) The geometric fluorescence intensity staining of GP33-responsive CD8+ T cells based on the ICCS assay. The left graphs show gMFI for IFN; the middle graphs show gMFI for IL-2 expression; the right graphs show gMFI of TNF expression. Each symbol represents an individual mouse, compiled from 2-3 experiments. A two-tailed Student's t-test was used to evaluate significance with *P <0.05; **P <0.01; ***P <0.001.