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Human Invariant NKT Cell Subsets Differentially Promote Differentiation, Antibody Production, and T Cell Stimulation by B Cells In Vitro

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Invariant NK T (iNKT) cells can provide help for B cell activation and Ab production. Because B cells are also capable of cytokine production, Ag presentation, and T cell activation, we hypothesized that iNKT cells will also influence these activities. Furthermore, subsets of iNKT cells based on CD4 and CD8 expression that have distinct functional activities may differentially affect B cell functions. We investigated the effects of coculturing expanded human CD4$^+$, CD8α$^+$, and CD4$^-$CD8α$^-$ double-negative (DN) iNKT cells with autologous peripheral B cells in vitro. All iNKT cell subsets induced IgM, IgA, and IgG release by B cells without needing the iNKT cell agonist ligand α-galactosylceramide. Additionally, CD4$^+$ iNKT cells induced expansions of cells with phenotypes of regulatory B cells. When cocultured with α-galactosylceramide–pulsed B cells, CD4$^+$ and DN iNKT cells secreted Th1 and Th2 cytokines but at 10–1000-fold lower levels than when cultured with dendritic cells. CD4$^+$ iNKT cells reciprocally induced IL-4 and IL-10 production by B cells. DN iNKT cells expressed the cytotoxic degranulation marker CD107a upon exposure to B cells. Remarkably, whereas iNKT cell subsets could induce CD40 and CD86 expression by B cells, iNKT cell–matured B cells were unable to drive proliferation of autologous and alloreactive conventional T cells, as seen with B cells cultured in the absence of iNKT cells. Therefore, human CD4$^+$, CD8α$^+$, and DN iNKT cells can differentially promote and regulate the induction of Ab and T cell responses by B cells. *The Journal of Immunology*, 2013, 191: 1666–1676.

Initiation of T cell–dependent B cell responses involves engagement of Ag by the BCR, resulting in Ag internalization, processing, and cell-surface presentation on MHC molecules (1–3). Upon recognition of cognate peptide–MHC class II complexes, the T cell upregulates CD40L, which engages CD40 on the B cell, inducing proliferation and differentiation. The T cell also secretes cytokines that are required for Ig isotype switching. Cognate T cell–B cell interactions can result either in extrafollicular proliferation of B cells into short-lived plasmablasts that do not undergo affinity maturation and mediate transient innate-like responses (2) or germinal center proliferation of B cells, which undergo somatic hypermutation and affinity maturation, resulting in the generation of long-lived plasma cells or memory B cells (3).

Invariant NKT (iNKT) cells can provide help for B cell maturation and Ab production. iNKT cells are cytotoxic T cells that express a TCR composed of an invariant α-chain (Vα14Jα18 in mice and Vα24Jα18 in humans) that pairs with a limited number of β-chains and recognizes glycolipid Ags presented by the MHC class I–like molecule CD1d (4, 5). iNKT cells are thought to play central roles in innate and adaptive immunity through their ability to activate or induce differentiation of NK cells (6), dendritic cells (DC) (4, 7, 8), and T cells (9) and to release multiple Th cell–polarizing cytokines (10–13). iNKT cells can also regulate, enhance, and sustain humoral immune responses. In murine models, CD1d and iNKT cells are required for the generation of protective Ab responses against pathogens, including *Plasmodium falciparum* (14), *Streptococcus pneumoniae* (15), and *Borrelia* species (16). CD1d and iNKT cells are also required for the production of allergen-specific IgE in an experimental asthma mouse model (17). The adjuvant effect of iNKT cells on humoral immune responses is Ag specific. Coadministration of the iNKT cell agonist ligand α-galactosylceramide (α-GC) with immunizing Ag to mice results in enhanced production of Abs specific for the Ag (18–20). This help provided by iNKT cells results in the induction of long-lived Ab-secreting plasma cells, affinity maturation, and the generation of memory B cells (20–22). iNKT cells can also provide help for B cells specific for lipid-containing Ags internalized through the BCR (23, 24). Such B cell help results in the formation of extrafollicular plasmablasts and germinal centers, affinity maturation, and robust IgG Ab responses but not long-lived memory cells (25).

Although iNKT cells express semi-invariant TCRs, they can be divided into distinct populations based on CD4 and CD8 expression. Humans have varying ratios of CD4$^+$CD8$^-$ (CD4$^+$), CD4$^-$

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Abbreviations used in this article: Breg, regulatory B cell; CBA, cytometric bead array; DC, dendritic cell; DN, double-negative; α-GC, α-galactosylceramide; FMO, fluorescence minus one (flow cytometry control); iDC, immature dendritic cell; iNKT, invariant NKT; MFI, mean fluorescence intensity; MZB, marginal zone B cell; PD-1, programmed cell death-1; PPD, purified protein derivative of tuberculin; SEB, Staphylococcal enterotoxin B; T_{FH}, follicular Th.

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CD8α$^-$β$^-$ (double-negative [DN]), and CD4$^-$CD8α$^+$β$^-$ (CD8α$^+$) iNKT cells (11, 13, 26). CD4$^+$ iNKT cells release the most Th2 cytokines, and CD8α$^+$ and DN iNKT cells predominantly exhibit Th1 phenotypes and cytotoxic activity (11, 13, 27). To date, two studies (28, 29) have examined the relative contributions of human iNKT cells subsets to B cell help and found that both CD4$^+$ and CD4$^-$ iNKT cells similarly induced B cell proliferation, but CD4$^+$ iNKT cells induced higher levels of Ab production.

In addition to their roles in Ab production, B cells are potent APCs that can prime CD4$^+$ T cells without the participation of DC or macrophages (30). Similar to DC, B cells can produce both Th1- and Th2-type cytokines and can be polarized toward one or the other subset subsequent to interaction with CD4$^+$ Th1 or Th2 cells (31). The unique abilities of iNKT cells to selectively secrete Th1, Th2, Th17, or regulatory T cell cytokines (10–13) and to induce DC maturation (7, 8, 32) led us to hypothesize that iNKT cells may exert stimulatory and/or regulatory control over Ag presentation and T cell activation by B cells. In this study, we have examined the outcomes of culturing human peripheral B cells with expanded autologous iNKT cells or sorted CD4$^+$, CD8α$^+$, and DN iNKT cell subsets in vitro in the absence or presence of α-GC. We show that the iNKT cell subsets differentially induce phenotypic differentiation, Ab secretion, and T cell stimulation by B cells. We also show that CD4$^+$ iNKT cells promote the development of cells with phenotypes of regulatory B (Breg) cells and the production of IL-10 by some B cells. Thus, CD4$^+$, CD8α$^+$, and DN iNKT cells can differentially promote T cell or Ab responses via their interactions with B cells. This observation has implications for iNKT cell–based therapies for cancer and autoimmune disease, which may require the selective targeting of functionally distinct subsets of iNKT cells.

Materials and Methods

Abs and flow cytometry

Fluorochrome-conjugated mAbs specific for human CD1d, CD3, CD4, CD5, CD8α, CD19, CD20, CD22, CD24, CD27, CD38, CD40, CD58, CD69, CD80, CD83, CD86, CD95, CD107a, HLA-DR, IFN-γ, IL-4, IL-10, IL-13, IL-21, the TCR Vα24 and Vβ11 chains, the CDR3 of the iNKT cell TCR (6B11), CXCR5, programmed cell death-1 (PD-1), and isotype control mAbs were purchased from Immunotools (Friesoythe, Germany), eBioscience (Hatfield, U.K.), Bio Legend (San Diego, CA), and BD Biosciences (Oxford, U.K.). A total of 10^5 cells were labeled with mAbs and analyzed using a CyAN ADP flow cytometer (Beckman Coulter, High Wycombe, U.K.). Data were analyzed with the Summit v4.3 software (DakoCytomation) and FlowJo v7.6 (Tree Star). In cocultures of expanded iNKT cells and B cells, iNKT cells were analyzed by gating on the CD3$^+$6B11$^+$ lymphocytes and on their CD4$^+$, CD8$^+$, and DN subsets. Follicular Th (T_{FH}) cells were defined as CXCR5$^+$PD-1$^+$ or IL-21$^+$. B cells were analyzed by gating on CD19$^+$ lymphocytes, and B cell subsets were defined as naive (CD27$^-$IgD$^+$), unswitched memory (CD27$^+$IgD$^+$), switched memory (CD27$^+$IgD$^-$), CD27$^-$ memory (CD27$^-$IgD$^-$) B cells, and two putative Breg cell subsets (CD1d^{hi}CD5$^+$ and CD24^{hi}CD38^{hi}). Single stained controls were used to set compensation parameters, and fluorescence-minus-one (FMO) and isotype-matched Ab controls were used to set analysis gates.

Isolation of human B cells

PBMC were isolated from blood samples obtained from healthy donors or from buffy coat packs (kindly provided by the Irish Blood Transfusion Service) by density gradient centrifugation over Lymphoprep (Nycomed Pharma, Oslo, Norway). B cells were purified by magnetic bead sorting using CD19 microbeads (Miltenyi Biotec, Bergisch Gladbach, Germany), and purity of B cells was determined to be >99% by flow cytometric analysis of CD20 expression. Enriched B cells were cryopreserved or maintained in iNKT cell medium, which consisted of RPMI 1640 containing 0.05 mM L-glutamine, 10% v/v HyClone FBS (Thermo-Scientific, Logan, UT), 0.02 M HEPES buffer, 100 U/ml penicillin, 100 μg/ml streptomycin, 2.5 μg/ml amphotericin B Fungizone, 1× MEM nonessential amino acids, and 0.05 mM 2-ME (Life Technologies BRL, Paisley, U.K.).

Generation of monocyte-derived DC

Monocytes were enriched to >90% purity from PBMC by positive selection using CD14 microbeads (Miltenyi Biotec). The monocytes were allowed to differentiate into immature DC (iDC) by culturing them for 6 d in the presence of GM-CSF and IL-4 as described previously (32). Flow cytometry was used to verify that differentiation into iDC had taken place and cells expressed HLA-DR and CD11c but not CD14.

Generation of iNKT cell lines

iNKT cells were enriched from PBMC by staining with a PE-conjugated anti-iNKT cell mAb (clone 6B11) followed by positive selection of the PE-positive cells by magnetic bead separation (Miltenyi Biotec). In later experiments, anti-iNKT cell microbeads were used. Enriched iNKT cells were then purified to >99% purity by flow cytometric sorting of CD3$^+$ Vα24$^+$Vβ11$^+$ cells using a MoFlo XDP Cell Sorter (Beckman Coulter). Sorted iNKT cells were cultured in iNKT cell medium and expanded by one of two methods described previously (13, 32). In the first method, iNKT cells were subjected to a single stimulation with plate-bound anti-CD3 (HIT3A) mAb (BD Biosciences) in the absence of irradiated feeder cells and cultured in the presence of rIL-2. In the second method, iNKT cells were stimulated with PHA in the presence of irradiated allogeneic PBMC and IL-2. Purity and phenotype of iNKT cell lines were assessed by flow cytometry after staining the cells with mAbs specific for CD3, 6B11, CD4, and CD8. Both methods resulted in 750–1000-fold enrichment of iNKT cells and yielded cell lines of which >98% displayed 6B11$^+$CD3$^+$ phenotypes (Fig. 1A). iNKT cell lines were phenotyped for expression of CD4 and CD8α (Fig. 1B) and means of 20 ± 21, 68 ± 26, and 11 ± 8% of 6B11$^+$ cells were CD4$^+$, DN and CD8α$^+$, respectively (Fig. 1C). Expanded iNKT cell lines were further sorted into CD4$^+$, CD8$^+$, and DN cells by MoFlo (Beckman Coulter) cell sorting.

Coculture of B cells with iNKT cells

B cells were cocultured with iNKT or as controls non-iNKT cells (total PBMC expanded with anti-CD3 mAb or PHA and IL-2 as done with iNKT cells) for 3 or 10 d at 1:1 ratios in 96-well round-bottom plates (Corning Life Sciences) at cell densities of 10^6 cells/ml. The following stimulators or blockers were added: 100 ng/ml α-GC (Funakoshi, Tokyo, Japan), 10 ng/ml PMA, and 1 μg/ml ionomycin (both from Sigma-Aldrich) and 10 μg/ml each of anti-CD1d, anti-CD40, anti-CD154, anti–IL-4, and anti–IL-13 mAb. Before adding to cultures, α-GC was subjected to heating, sonication, and vortexing as described previously (13). Supernatants were harvested and frozen at −20°C until they were analyzed for cytokine

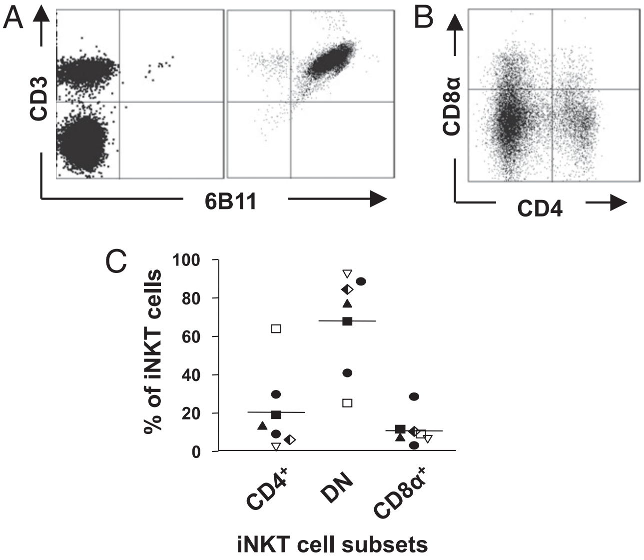

FIGURE 1. Expansion of iNKT cell subsets. (**A**) Flow cytometric analysis of CD3 and the Vα24Jα18 TCR (6B11) expression by freshly isolated PBMC and a 6-wk-old iNKT cell line. Plots are representative of iNKT lines generated from 10 healthy donors. (**B**) Flow cytometric analysis of CD4 and CD8 expression by expanded iNKT cells after electronically gating on CD3$^+$6B11$^+$ cells. (**C**) Mean proportions of CD4$^+$, DN, and CD8$^+$ iNKT cell subsets found in seven iNKT cell lines.

and Ig production. Cells were recovered for phenotypic analysis by flow cytometry or for use as stimulators of T cells.

Analysis of cytokine and Ab secretion

Cytometric bead array (CBA) kits were used to quantify the levels of cytokines and Igs in supernatants from the B–iNKT cell cocultures, according to the manufacturer's instructions (BD Biosciences). The cytokines assayed for were IFN-γ, IL-2, IL-4, IL-5, IL-6, IL-10, IL-12p70, and IL-13. The Igs assayed for were IgA, IgM, total IgG, IgG1, IgG2, and IgE. Flow cytometric data were generated using a CyAN ADP flow cytometer (Beckman Coulter), and geometric means of the individual bead populations were analyzed using Summit v4.3 software (DakoCytomation). GraphPad Prism v5.0 (GraphPad Software, La Jolla, CA) was used to draw standard curves and obtain sample concentration values.

Analysis of intracellular cytokine production by iNKT cell and B cell subsets

Total B cells were cocultured for 3 d in medium alone or with equal numbers of sorted CD4$^+$ iNKT cells in the absence or presence of α-GC as described above. Monensin (0.05 mM; Sigma-Aldrich) was added for the last 4 h to promote intracellular accumulation of cytokines. Cells were then washed and stained for cell surface expression of 6B11, CD19, CD1d, CD5, CD24, and CD38 and intracellular expression of IFN-γ, IL-10, IL-4, and IL-21 using fluorochrome-conjugated mAb obtained from BD Biosciences or eBioscience and analyzed by flow cytometry (13).

Cytotoxicity assays

Cytolytic degranulation by iNKT cells in response to B cells in the absence and presence of α-GC was examined by analysis of cell-surface CD107a expression. iNKT cells and B cells were cocultured for 4 h at 1:1 ratios in the presence of anti-CD107a PE-Cy7 mAb. Monensin (2 μM) was added after 1 h to prevent proteolysis of the mAb conjugate upon reinternalization of CD107a. Frequencies of CD107a expression by iNKT subsets were determined by flow cytometry after electronically gating on CD4$^+$, DN, and CD8α$^+$ subsets.

Analysis of the capacity of B cells to drive T cell proliferation

B cells were cocultured with equal numbers of autologous iNKT cells at densities of 10^6 cells of each type per milliliter in the presence or absence of 100 ng/ml α-GC for 3 d. B cells and iNKT cells were also cultured separately in medium alone as negative controls. The cocultured cells were harvested, washed, and examined for expression of CD40, CD69, CD80, CD83, CD86, and HLA-DR by flow cytometry or used as stimulators for autologous or allogeneic conventional T cells that were enriched by magnetic selection using CD3 microbeads (Miltenyi Biotec). The T cells were labeled using the CellTrace Violet Cell Proliferation Kit following the manufacturer's instructions (Invitrogen, Paisley, U.K.) and cultured with the B/iNKT cells at ratios of 3:1 with the following stimuli: medium only (negative control), 10 μg/ml purified protein derivative of tuberculin (PPD; Statens Serum Institut, Copenhagen, Denmark) (4), 1 μg/ml Staphylococcal enterotoxin B (SEB; Sigma-Aldrich) (4), or 5 μg/ml PHA (Sigma-Aldrich). Proliferation of the T cells was assayed by flow cytometric examination of dilution of the CellTrace dye after 6 d in culture. Acquired data were analyzed using FlowJo v7.6 (Tree Star).

Statistical analyses

Statistical analysis was performed using GraphPad Prism v5.0 (GraphPad). For comparison between two groups, the Mann–Whitney *U* test was used to compare unpaired data, and the Wilcoxon matched-pairs test was used to compare paired data. For comparison among three or more groups, the Kruskal–Wallis test was used to compare unpaired data, and the Friedman's test was used to compare paired data. Dunn's multiple comparison tests were performed post hoc to compare individual groups within an experiment. Two-way ANOVA with post hoc Bonferroni's test was used to compare the effect of treatments.

Results

CD1d is uniformly expressed across all B cell subsets

PBMC from seven healthy donors were stained with mAbs specific for CD19 and CD1d and CD5, CD22, CD38, or CD27, which detect B-1, mature, plasma, and memory B cells, respectively (Fig. 2). CD1d expression by each B cell subset was determined by comparing the intensity of staining with anti-CD1d mAb with that of the corresponding FMO control, in which the anti-CD1d mAb was omitted (Fig. 2A). Up to 30% of circulating B cells expressed phenotypes associated with plasma cells, whereas 19–44% were B-1 cells and 12–31% were memory cells (Fig. 2B). CD1d was expressed at the cell surface of similar proportions (48–92%) of each B cell subset. Memory B cells displayed the highest proportion of CD1d expression (Fig. 2C), whereas the mean fluorescence intensity (MFI) of CD1d expression was also highest on this B cell subset. (Fig. 2D). One-way ANOVA showed no significant difference between the mean proportions of or MFI of CD1d expression on each B cell subset. Whereas CD1d expression by B cells is reported to be downregulated by activation (33), we found that coculturing with iNKT cells did not affect the level of CD1d expression (Fig. 2E).

CD4$^+$, DN, and CD8α$^+$ iNKT cells can induce secretion of IgG, IgA, and IgM, but not IgE, by B cells

iNKT cells can provide help to B cells for the production and secretion of Abs in vivo (18–24). We investigated whether sorted subsets of CD4$^+$, DN, and CD8α$^+$ iNKT cells differed in their capacity to induce Ab production. Initially, B cells were cultured with total iNKT cells or non-iNKT cells in the absence of added Ag, and cell supernatants were removed after 3 d (data not shown) or 10 d (Fig. 3A) and assayed for Ab production by multiplex CBA analysis. Relative to B cells cultured alone, there was increased production of IgA and IgM ($p < 0.05$) after 3 d of culture with iNKT cells and of total IgG ($p < 0.01$), IgM, and IgA ($p < 0.05$) after 10 d of B cell coculture with iNKT (Fig. 3A). In contrast, non-iNKT cells did not induce the release of these Abs by the same B cells. No IgE was detected in any of the stimulations or cocultures (data not shown). When sorted subsets of CD4$^+$, DN, and CD8$^+$ iNKT cells were cultured for 10 d with B cells, all three subsets induced IgM, IgA, and IgG production (Fig. 3B). Surprisingly, the addition of α-GC to the cocultures did not result in enhanced Ab production. The activation of B cells in the absence of α-GC may thus be due to the presence of a self-glycolipid presented by CD1d on the B cell.

To investigate the requirements for cell–cell contact and for CD1d and cytokines in iNKT cell–mediated B cell help for Ab production, B cells were cultured alone or with equal numbers of total iNKT cells for 10 d together or separated using transwell plates and in the absence or presence of blocking Abs against CD1d, IL-4, IL-13, CD40, or CD154. Supernatants from the cocultures were removed and assayed for IgG, IgM, and IgA release. When B cells and iNKT cells were separated in transwell plates or when blocking Abs against CD1d were added to the iNKT–B cell cocultures, Ab secretion was inhibited (see Fig. 3C for IgA). When anti–IL-4, anti–IL-13 (Fig. 3C), anti-CD40, or anti-CD154 mAbs (Fig. 3D) were added to the cultures, there was no inhibition of IgG, IgM, or IgA release, and the anti-CD40 mAb may have a weak agonistic effect on B cell activation. Therefore, all three subsets of human iNKT cells can provide B cell help for Ab production by a mechanism that requires cell contact and CD1d but not α-GC and does not appear to require CD40–CD154 interactions or Th2 cytokine secretion.

CD4$^+$ iNKT cells induce the expansion of unswitched memory and CD1d^{hi}CD5$^+$ B cells

Total B cells were cultured for 3 or 10 d in medium alone or with equal numbers of expanded total, CD4$^+$, CD8$^+$, or DN iNKT cells or non-iNKT cells (PBMC expanded by anti-CD3 mAb and IL-2). Changes in the percentages of naive (CD27$^-$IgD$^+$), unswitched memory (CD27$^+$IgD$^+$), switched memory (CD27$^+$IgD$^-$), and

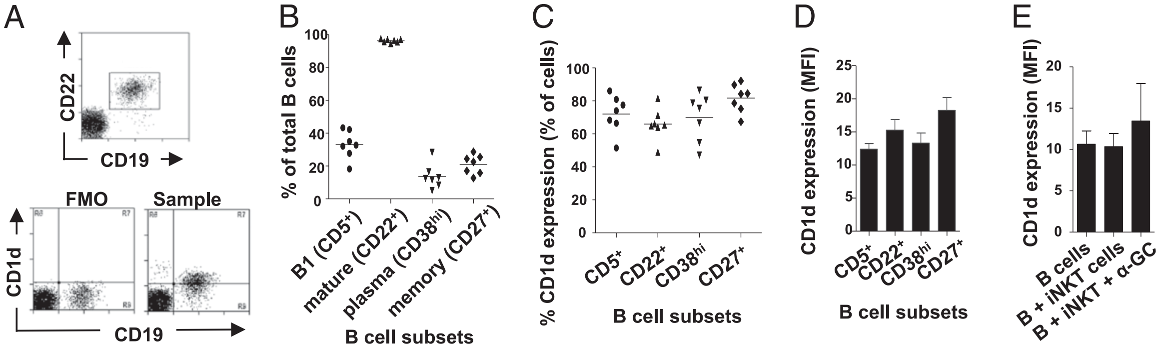

FIGURE 2. CD1d is uniformly expressed across all human B cell subsets. (**A**) Representative flow cytometry dot plot showing the identification of B cell subsets and the gating strategy for measuring CD1d expression by B cell subsets (*top panel*). The *bottom left panel* shows the FMO control lacking the anti-CD1d mAb, whereas the *bottom right panel* shows CD1d expression. (**B**) Proportions of B cell subsets in peripheral blood of seven donors. (**C**) Proportions of B cell subsets that express cell-surface CD1d. Horizontal lines represent means from seven donors. (**D**) Average (± SEM) MFI of CD1d expression by B cell subsets. One-way ANOVA showed that there were no significant differences in CD1d expression between the subsets. (**E**) Average (± SEM) MFI of CD1d expression by total B cells cultured for 3 d in the absence and presence of iNKT cells and α-GC.

$CD27^-$ memory ($CD27^-IgD^-$) B cells and two putative Breg cell subsets ($CD1d^{hi}CD5^+$ and $CD24^{hi}CD38^{hi}$) (34, 35) were analyzed by flow cytometry. The expression of the T_{FH} ($CXCR5^+PD\text{-}1^+$) phenotype (36, 37) by the iNKT cells was also examined. Total and $CD4^+$ iNKT cells, but not $CD8^+$ nor DN iNKT cells, in the presence of α-GC induced modest expansions of unswitched memory B cells (28–46%) after 10 d with concomitant reductions in naive B cells (35–22%) by a mechanism that required cell–cell contact (data not shown). However, the numbers of switched and $CD27^-$ memory B cells were unaffected. Sorted $CD4^+$ iNKT cells also induced significant expansions of $CD1d^{hi}CD5^+$ B cells (Fig. 4A, 4B). In contrast, $CD8^+$ and DN iNKT cells induced upregulation of CD5 but not CD1d on B cells. Induction of $CD1d^{hi}CD5^+$ B cells by $CD4^+$ iNKT cells required cell–cell contact but not prior activation of the iNKT cells with α-GC. $CD4^+$ iNKT cells in the presence of α-GC also induced a moderate expansion of $CD24^{hi}CD38^{hi}$ B cells (Fig. 4B). These results provide evidence that resting $CD4^+$ iNKT cells may induce the differentiation of Breg cells in vitro.

Although iNKT cells provided B cell help for Ab secretion (Fig. 3), <2% of $CD4^+$, $CD8\alpha^+$, or DN expressed the $CXCR5^+$ $PD\text{-}1^+$ phenotype found on T_{FH} cells and murine iNKT cells (36, 37). The presence of B cells or α-GC did not significantly alter the frequencies of iNKT cells that express T_{FH} phenotypes (Fig. 4C).

B cells present α-GC to $CD4^+$ and DN iNKT cells resulting in the release of low levels of IFN-γ, TNF-α, IL-4, IL-5, IL-10, and IL-13

The ability of B cells to present α-GC to iNKT cells resulting in cytokine release was investigated by coculturing B cells alone or with autologous sorted $CD4^+$, DN, or $CD8^+$ iNKT cells in the absence or presence of α-GC. Cell supernatants were removed after 3 d and assayed for cytokine levels by multiplex CBA

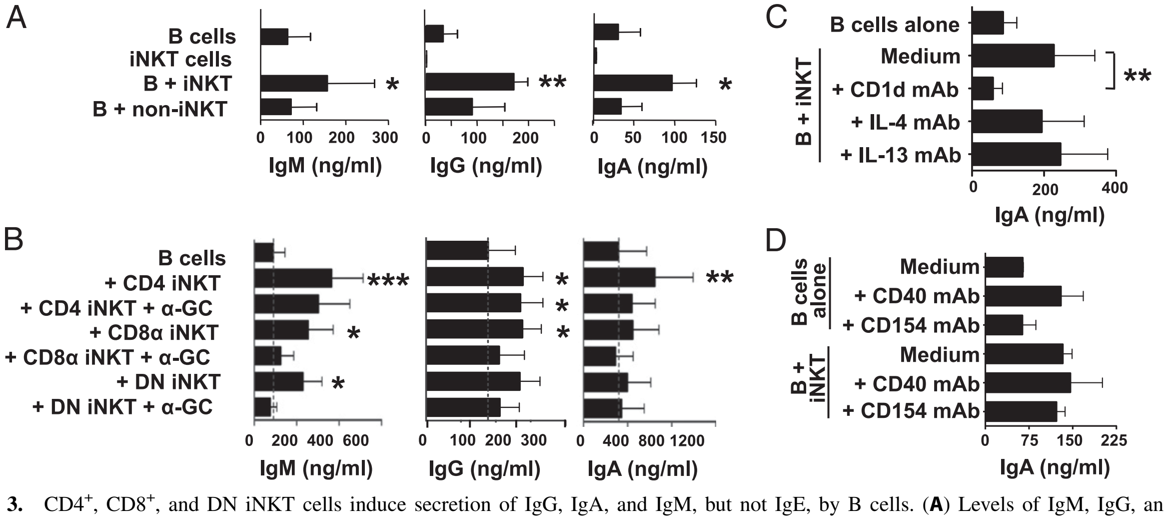

FIGURE 3. $CD4^+$, $CD8^+$, and DN iNKT cells induce secretion of IgG, IgA, and IgM, but not IgE, by B cells. (**A**) Levels of IgM, IgG, and IgA in supernatants from 10-d cultures of B cells, iNKT cells, and cocultures of B cells with iNKT cells or non-iNKT cells (PBMC expanded by anti-CD3 mAb and IL-2 stimulation). IgE was also assayed for and not detected in any cultures. Bars represent means ± SEM from three independent experiments. (**B**) Levels of IgM, IgG, and IgA released by B cells cultured for 10 d in medium alone or with $CD4^+$, $CD8^+$, or DN iNKT cells, in the absence or presence of 100 ng/ml α-GC. Results are means ± SEM from seven experiments. (**C** and **D**) Levels of IgA in supernatants of B cells cultured for 10 d in medium alone or with iNKT cells in the absence or presence of blocking mAbs specific for CD1d, IL-4, and IL-13 (C) and CD40 and CD154 (D). Results are means ± SEM from three and six donors for (C) and (D), respectively. $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$ compared with the levels released by B cells cultured in medium alone except where indicated by bars.

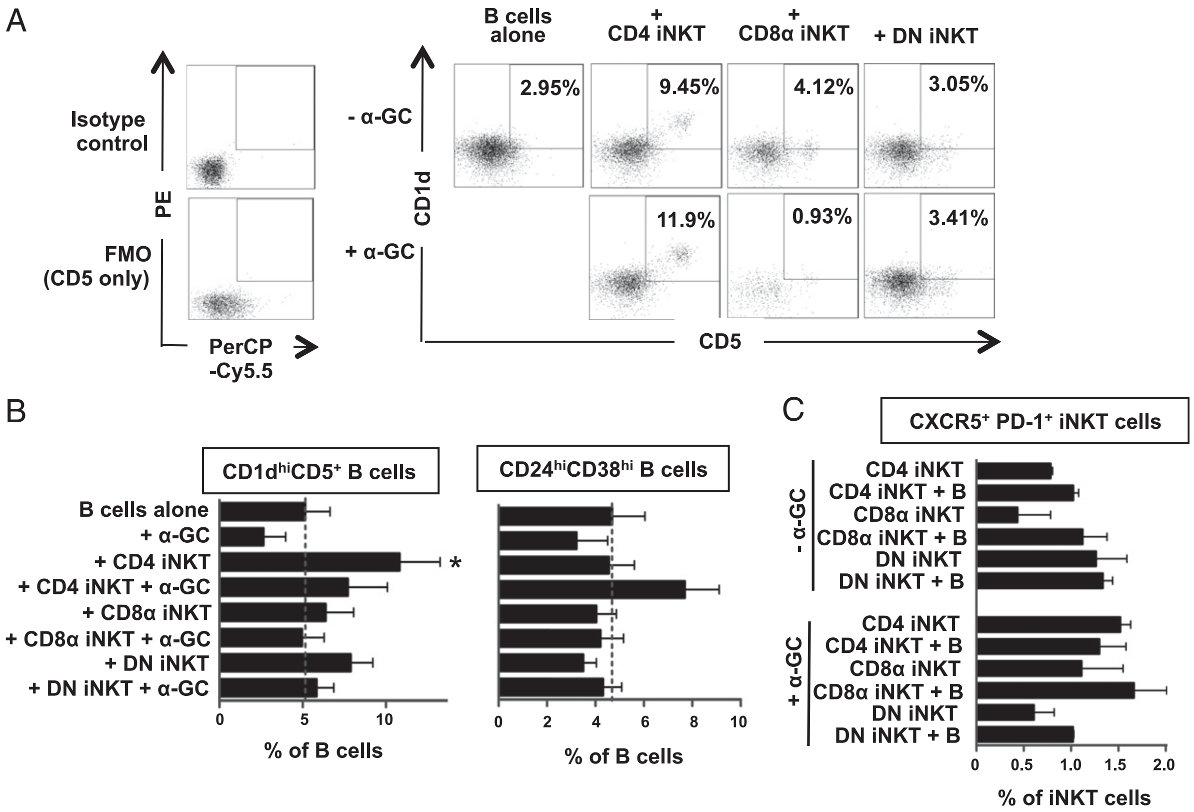

FIGURE 4. $CD4^+$ iNKT cells induce the expansion of $CD1d^{hi}CD5^+$ and $CD24^{hi}CD38^{hi}$ B cells. B cells from seven donors were cultured for 3 d in medium alone or with equal numbers of expanded $CD4^+$, $CD8^+$, or DN iNKT cells in the absence or presence of α-GC. (**A**) Representative flow cytometry dot plots showing isotype control mAb staining and FMO for CD1d mAb staining (*left panel*) and CD1d and CD5 expression (*right panel*) by gated $CD19^+$ cells. (**B**) Mean (± SEM) percentages of B cells that expressed $CD1d^{hi}CD5^+$ (*left panel*) or $CD24^{hi}CD38^{hi}$ (*right panel*) phenotypes. $^*p < 0.05$. (**C**) Mean (± SEM) percentages of iNKT cells that expressed $CXCR5^+PD\text{-}1^+$ T_{FH} phenotypes.

analysis. We found that coculturing B cells with any of the iNKT cell subsets in the absence of α-GC did not lead to significant increases in IFN-γ, TNF-α, IL-2, IL-4, IL-5, IL-10, or IL-13 release compared with B cells, iNKT cells, or non-iNKT cells cultured alone. When α-GC was present, low levels of IFN-γ, TNF-α, IL-4, IL-5, and IL-13, but not IL-2 nor IL-10, were released by the cocultures of B cells with $CD4^+$ or DN iNKT cells (Fig. 5A). Although $CD4^+$ iNKT cells induced the expansion of cells with phenotypes associated with Breg cells (Fig. 4), no IL-10 was detected in the supernatants of these cocultures. When monocyte-derived DC were used as APCs for α-GC, all subsets of iNKT cells released the above cytokines, including IL-10, with 100–1000-fold more IFN-γ and TNF-α and 10–100-fold more IL-4, IL-5, and IL-13 released compared with when B cells were used as APCs (Fig. 5B). It is unlikely that the low amounts of cytokines produced by cocultures of B cells and iNKT cells are due to contaminating monocytes or DC, because the B cells were enriched to purities of >99.5%, as shown by flow cytometric analysis of CD19 and CD20 expression. These results suggest that B cells can present α-GC to iNKT cells but are 10–1000 times less efficient than DC at stimulating cytokine production by the cells.

To determine the cellular sources of these cytokines and further investigate if the $CD1d^{hi}CD5^+$ B cells that were induced by $CD4^+$ iNKT cells have cytokine profiles typical of Breg cells, total B cells were cultured for 3 d in medium alone or with equal numbers of expanded $CD4^+$ iNKT cells in the absence or presence of α-GC. Monensin was added to the cultures for the final 4 h, and the expression of IFN-γ, IL-10, and IL-4 by gated $CD19^+$ (B) cells and $6B11^+$ (iNKT) cells was examined by flow cytometry. Upon stimulation with B cells pulsed with α-GC, most iNKT cells produced IFN-γ and IL-4, but these cytokines were produced by <2% of B cells (Fig. 5C). Interestingly, when B cells were cocultured with $CD4^+$ iNKT cells, up to 1% of the B cells and up to 2% of the iNKT cells expressed IL-10. However, due to the small numbers of $CD1d^{hi}CD5^+$ B cells, we were unable to determine with certainty if this putative Breg population was the source of B cell–derived IL-10. Thus, although B cells present α-GC to $CD4^+$ iNKT cells, resulting in Th1 and Th2 cytokine production, $CD4^+$ iNKT cells induce the expansion of B cells with phenotypes of Breg cells and can induce IL-10 production by some B cells.

The ability of iNKT cell subsets to produce the T_{FH} cell cytokine IL-21 was also tested by intracellular staining for IL-21 in iNKT cell subsets after exposure for 3 d to B cells in the presence and absence of α-GC. Fig. 5D shows that <2% of untreated $CD4^+$, $CD8\alpha^+$, and DN iNKT cells produced IL-21, and these frequencies were not changed by the addition of B cells or α-GC. Thus, although iNKT cells can provide B cell help for Ab production, <2% express classical T_{FH} cell phenotypes (Fig 4C) or cytokine profiles (Fig. 5D).

DN iNKT cells degranulate in the presence of B cells

To determine if subsets of iNKT cells can potentially kill autologous B cells, total iNKT cells were cultured with equal numbers of sorted B cells, and cytolytic degranulation by iNKT cell subsets was measured by CD107a externalization. Fig. 6 shows that $CD4^+$ and $CD8^+$ iNKT cells did not degranulate in response to B cells whether or not α-GC was present, but these cells expressed CD107a at the cell surface when stimulated with PMA and ionomycin. Surprisingly, DN iNKT cells displayed significant CD107a

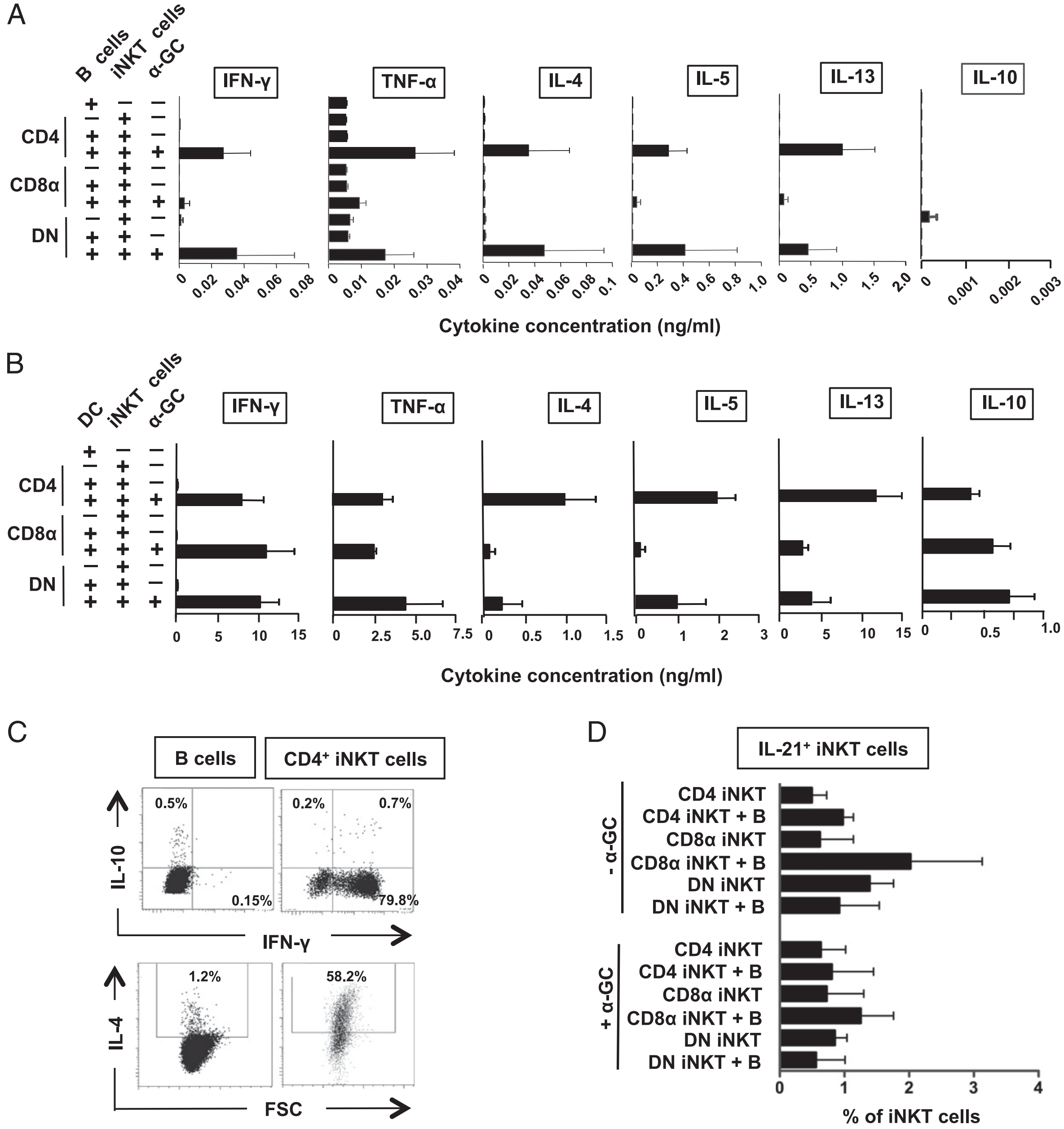

FIGURE 5. Cocultures of α-GC–pulsed B cells and CD4$^+$ or DN iNKT cells produce low levels of IFN-γ, TNF-α, IL-4, IL-5, IL-13, and IL-10. (**A**) Cytokine levels released by B cells, CD4$^+$, CD8$^+$, and DN iNKT cells and B cells cocultured for 3 d with autologous CD4$^+$, CD8$^+$, and DN iNKT cells in the absence or presence of α-GC. (**B**) Cytokine levels released by DC, iNKT cell subsets, and 3-d cocultures of DC and iNKT cells. (**C**) Flow cytometry dot plots showing intracellular expression of IFN-γ and IL-10 (*top panel*) and IL-4 (*bottom panel*) by gated B cells (*left panel*) and CD4$^+$ iNKT cells (*right panel*) cocultured for 3 d in the presence of α-GC. (**D**) Mean (± SEM) percentages of CD4$^+$, CD8$^+$, and DN iNKT cells that produced IL-21 after 3 d of culture with B cells in the absence and presence of α-GC. Bars represent means (± SEM) from three (A, B) or four (D) independent experiments.

expression in response to B cells, whether or not α-GC was present. Thus, it is likely that DN iNKT cells can kill autologous B cells.

iNKT cells induce expression of activation and costimulatory markers by B cells

To determine if iNKT cells can induce maturation of B cells into cells with APC phenotypes, total B cells were cultured for 3 or 10 d in medium alone, with PMA and ionomycin or with equal numbers of expanded iNKT cells or non-iNKT cells. Changes in cell-surface expression of CD40, CD83, CD86, CD69, CD80, and HLA-DR by total B cells and naive, unswitched memory, switched memory, CD27$^-$ memory B cells, and CD1d^{hi}CD5$^+$ and CD24^{hi} CD38^{hi} B cells were analyzed by flow cytometry. We observed increased expression of CD40 ($p < 0.05$), CD95 ($p < 0.01$), CD86 ($p < 0.05$), and CD83 (not significant), but not CD80 nor HLA-DR on total B cells after 3 d of coincubation with total iNKT cells (Fig. 7A). After 10 d of coincubation with iNKT cells, these markers were not expressed at significantly higher levels than on B cells cultured alone. When non-iNKT cells were substituted for iNKT cells, the levels of the above-mentioned markers were similar to those on B cells cultured alone (Fig. 7A). CD40 and CD86 were upregulated on naive, unswitched memory, switched memory, CD27$^-$ memory B cells, and the two putative Breg cell subsets (CD1d^{hi}CD5$^+$ and CD24^{hi}CD38^{hi}) (data not shown).

When sorted CD4$^+$, DN, and CD8$^+$ iNKT cells were cultured with the B cells, only the CD4$^+$ subset was found to significantly

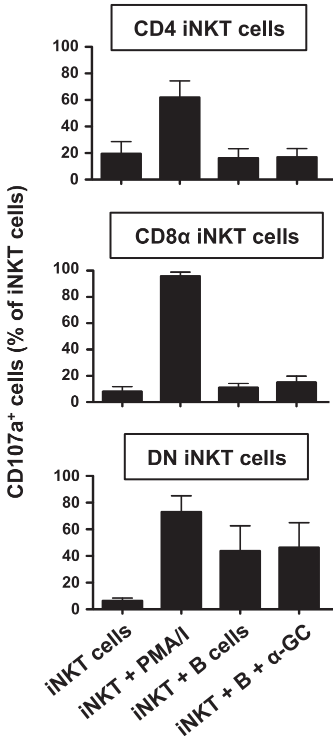

FIGURE 6. DN iNKT cells can kill autologous B cells. Mean (± SEM) percentages of CD4$^+$ (*top panel*), CD8α$^+$ (*middle panel*), and DN (*bottom panel*) iNKT cells from four donors that express cell-surface CD107a after culture in medium alone or with autologous B cells in the absence and presence of PMA and ionomycin (PMA/I) and α-GC.

induce CD40 and CD86 expression, and this occurred only when α-GC was present. CD8$^+$ and DN iNKT cell subsets also weakly induced CD86 expression, but whereas CD4$^+$ and DN iNKT cells required the presence of α-GC to do so, CD8$^+$ iNKT cells did not (Fig. 7B). Therefore, iNKT cells induce the expression of activation and costimulatory molecules by B cells, but the CD4$^+$, DN, and CD8$^+$ iNKT cell subsets differ in their abilities to do so and in their requirements for ligand activation.

The requirements for cell–cell contact, CD1d, and cytokines in iNKT cell–mediated upregulation of CD40, CD83, and CD86 expression by B cells were tested using transwell plates and in the absence or presence of blocking mAbs against CD1d, IL-4, or IL-13. When B cells and iNKT cells were separated in transwell plates or when anti-CD1d blocking Abs were added to the iNKT–B cell cocultures, the upregulation of all three markers was reduced (Fig. 7C). Blocking IL-13 resulted in moderate inhibition of CD86 expression only, but blocking IL-4 had no effect on the expression of any of these markers.

iNKT cells prevent the induction of T cell proliferation by B cells

The effect of total iNKT cells on the ability of B cells to promote proliferation of autologous and allogeneic T cells was investigated using the CellTrace Violet Cell Proliferation assay (Invitrogen). B cells that were cultured in medium alone were able to induce proliferation of autologous T cells in the absence of Ag and to a greater degree in the presence of PPD, SEB, or PHA (Fig. 8). However, B cells that were precultured with iNKT cells were greatly reduced in their ability to induce T cell proliferation. Nonspecific and PPD-stimulated T cell proliferation was abrogated by the presence of iNKT cells, whereas SEB-specific T cell proliferation was not. Allogeneic T cell proliferation was also abrogated by iNKT cells. This inhibition of B cell–stimulated T cell proliferation occurred whether or not α-GC was present in the iNKT–B cell cocultures.

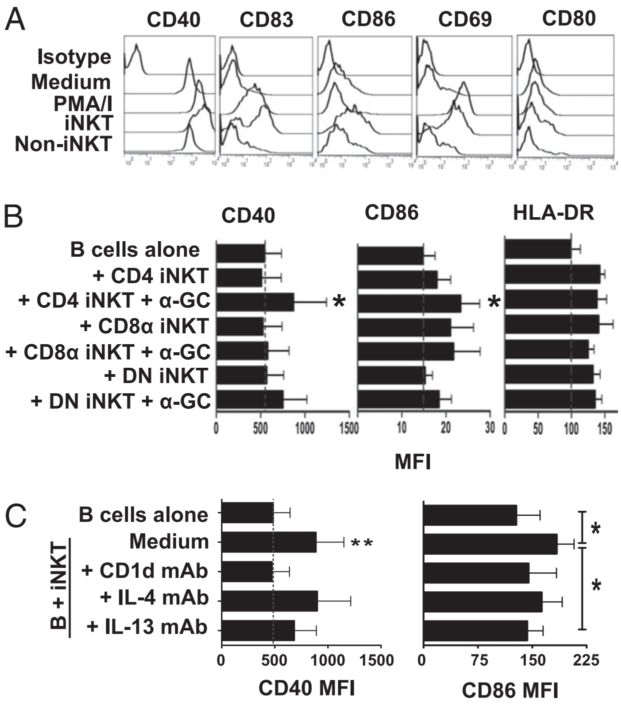

FIGURE 7. NKT cells induce upregulation of activation and costimulatory molecules by B cells. B cells were cultured in medium alone, with PMA and ionomycin, or with equal numbers of expanded iNKT cells or non-iNKT cells for 3–10 d. Changes in cell-surface expression of CD40, CD83, CD86, CD69, and CD80 by gated B cells (CD19$^+$) were analyzed by flow cytometry. (**A**) Offset histogram overlays showing mean fluorescence intensity (MFI) of staining of gated B cells with mAbs specific for the indicated markers or isotype control mAb (top histograms) after culturing B cells (from second from top to bottom histograms) in medium alone or with PMA and ionomycin, iNKT cells, or non-iNKT cells. (**B**) Bar graphs showing average (± SEM) MFI of staining for CD40 and CD86 expression by B cells from seven donors after incubation for 3 d with medium alone or with autologous CD4$^+$, CD8$^+$, or DN iNKT cells, in the absence or presence of 100 ng/ml α-GC. (**C**) MFI of CD40 (*left panel*) and CD86 (*right panel*) expression by B cells from six donors cultured for 3 d in medium alone or with iNKT cell in the absence or presence of blocking mAbs specific for CD1d, IL-4, and IL-13. *$p < 0.05$ compared with MFI on B cells cultured in medium alone, **$p < 0.01$.

Discussion

iNKT cells provide cognate and noncognate help for lipid-reactive and protein-reactive B cells. They are required for the generation of protective Ab responses against some murine pathogens (14–16), and they dramatically augment Ab responses to coadministered Ags in vivo (18–22). These findings have led to interest in iNKT cells and their ligands as adjuvants for the development of vaccines and immunotherapies (38, 39). However, despite their name, iNKT cells are heterogeneous and multifunctional in nature. Human CD4$^+$, CD8α$^+$, and DN iNKT cells can release Th1 (IFN-γ and TNF-α) and Th2 (IL-4, IL-5, and IL-13) cytokines when activated with α-GC presented by CD1d$^+$ cells. The relative amounts of the cytokines follow a striking CD8α > DN > CD4 pattern for Th1 and a CD4 > DN > CD8α pattern for Th2, whereas CD4$^+$ iNKT cells, only, produce IL-9 and IL-10 (11, 13, 27). These variable Th cell cytokine profiles prompted us to compare the relative abilities of CD4$^+$, CD8α$^+$, and DN iNKT cell lines to provide help for B cell differentiation and Ab production in vitro. We also have investigated the influence iNKT cell subsets

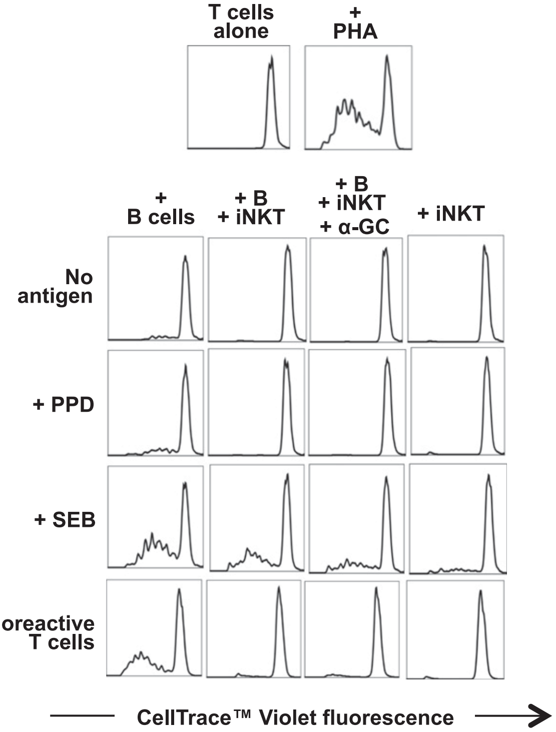

FIGURE 8. iNKT cells inhibit the induction of T cell proliferation by B cells. B cells were cocultured with equal numbers of autologous iNKT cells in the absence or presence of 100 ng/ml of α-GC for 3 d. B cells and iNKT cells were also cultured separately in medium alone as negative controls. The cocultured cells were harvested, washed, and used as stimulators of sorted autologous or allogeneic conventional CD3$^+$ T cells that were labeled using the CellTrace Violet (Invitrogen). The T cells were cultured with the B/iNKT cells at a ratio of 3:1 with medium only, 10 μg/ml PPD, 1 μg/ml SEB, or 5 μg/ml PHA. Proliferation of the T cells was assayed by flow cytometric examination of dilution of the CellTrace dye after 6 d in culture. Plots are representative of three independent experiments.

have on cytokine production, Ag presentation, and T cell activation by B cells.

Two previous in vitro coculture studies of B cells with fresh (29) and expanded (28) human iNKT cells and one on murine iNKT cells (40) have shown that iNKT cells can induce Ab production by human B cells in vitro. We found that all subsets of expanded iNKT cell lines induced the secretion of IgG (both IgG1 and IgG2), IgA, and IgM by autologous B cells. Also observed by Galli and coworkers (28), we found that IgE was not induced by any of the three iNKT cell subsets. This may reflect a need for conventional CD4$^+$ T cells, which are required for iNKT cell–mediated IgE production by murine B cells (41). iNKT cell–mediated help for B cells required cell–cell contact and CD1d, but did not appear to involve CD40–CD154 interaction, and it was not inhibited by neutralizing Abs against IL-4 or IL-13. These findings compare and contrast with those from in vivo studies in mice immunized with α-GC and protein Ag, which showed that iNKT cell–mediated B cell help required B cell expression of CD1d (21, 24, 42) and CD40 (24, 37) but did not require IL-4 (24). iNKT cell–mediated enhancement of Ab responses in vivo also required DC but did not require the expression of CD1d by DC (43). Another difference between these in vivo models of α-GC–mediated B cell help and our system is that α-GC was not required for iNKT cell–mediated B cell help in vitro. Galli and coworkers (28) also found that human CD4$^+$ iNKT cells, in the absence or presence of Ag, induced IgM production by B cells in vitro. Our findings confirm that the direct interaction between iNKT cells and B cells is sufficient to stimulate Ab production in vitro and that exogenous Ag is not required.

The ability of iNKT cells to provide B cell help for Ab production prompted us to examine whether these iNKT cells express CXCR5$^+$PD-1$^+$ phenotypes of T$_{FH}$ cells or produce IL-21, attributes that are associated with murine iNKT cells stimulated in vivo with α-GC (25, 36, 37). We found that up to 2% of expanded iNKT cells expressed T$_{FH}$ phenotypes or released IL-21, and this frequency was not increased by coculturing them with B cells in the absence or presence of α-GC. Similar proportions of iNKT cells displaying T$_{FH}$ phenotypes were found in mice immunized with Ag and α-GC (36, 37).

The ability of iNKT cells to induce Ab secretion by B cells highlights them as potential targets for therapeutic boosting of Ab responses in vaccines and infections or inhibition of pathogenic Ab production in autoimmune and allergic disease. Devera and coworkers (42) exploited iNKT help to B cells to enhance and sustain neutralizing Ab responses toward the *Bacillus anthracis* lethal toxin, which led to sustained survival and good health in mice challenged with the toxin. However, because of the multiple effector and immunoregulatory activities of iNKT cells, a complete understanding of the mechanisms underlying the interaction between iNKT cells and B cells is essential to predict or program the outcomes in vivo.

Activation of human iNKT cells requires the presence of immature but not mature B cells (44). However, we found that CD1d is expressed at comparable levels by mature, plasma, memory, and B-1 B cells, suggesting that all B cell subsets can present glycolipids to iNKT cells. CD4$^+$ iNKT cells were found to promote expansions of unswitched (IgD$^+$) memory B cells in a contact-dependent manner, resulting in decreased frequencies of naive B cells. Despite inducing Ab release by B cells, none of the iNKT cell subsets induced significant expansions of switched (IgD$^-$) memory B cells or the expression of IgM or IgG by any memory B cell subset. This suggests that iNKT cells promote Ab release by class-switched memory B cells rather than inducing class switching. Thus, it appears that iNKT cells may interact differently with naive and memory B cells, promoting differentiation of naive B cells into unswitched memory cells that are not required for iNKT cell activation while promoting differentiation of switched memory B cells into Ab-secreting plasma cells. Future experiments involving stimulation of B cells with iNKT cell subsets followed by detection of specific Ab-secreting memory B cells are required to confirm that iNKT cells can restimulate memory B cells.

We investigated if iNKT cells could induce the expansion of putative Breg cells. The CD1d^{hi}CD5$^+$ B cell phenotype defines a subset of murine B cells that downregulate immune responses via secretion of IL-10 and inhibit the development of autoimmune disease (34, 45, 46). In humans, an IL-10–producing B cell population that inhibits Th1 cell differentiation resides in the CD24^{hi}CD38^{hi} B cell compartment, and this subset is impaired in patients with systemic lupus erythematosus (35, 47). The majority of human CD1d^{hi}CD5$^+$ B cells are reported to be contained in the CD24^{hi}CD38^{hi} B cell subset (35); therefore, we investigated both subsets as putative Breg cells. We found that coculturing B cells with total iNKT cells did not significantly affect CD1d expression. However, CD4$^+$ iNKT cells induced the expansion of a population of CD1d^{hi}CD5$^+$ B cells by a mechanism that required cell–cell contact but not activation of the iNKT cells with α-GC. CD4$^+$ iNKT cells in the presence of α-GC also induced a moderate expansion of CD24^{hi}CD38^{hi} B cells. Although, we did not detect IL-10 in the supernatants of cocultures of CD4$^+$ iNKT cells with

B cells using multiplex CBA analysis, up to 1% of the B cells in these cultures expressed intracellular IL-10. IL-10 production is a hallmark feature of Breg cells (34, 35, 48–50). We were unable to show convincingly that this IL-10 was produced by the CD1d^{hi} CD5^{+} subset of B cells; however, our data indicate that CD4^{+} iNKT cells induced IL-10 production by *some* B cells, suggesting that they promote Breg cell differentiation. We also found that up to 1 ng/ml of IL-10 was released by cocultures of DC with all subsets of iNKT cells, suggesting that iNKT cells can induce regulatory DC as well as B cells.

DC can present α-GC to iNKT cells resulting in the rapid secretion of Th1 and Th2 cytokines in vivo and in vitro (7, 8, 13, 32) (Fig. 5B). However, experiments aimed at demonstrating that B cells can similarly present α-GC and induce cytokine production by iNKT cells have been conflicting. Bialecki and coworkers (51) reported no IFN-γ or IL-4 production by cocultures of murine iNKT cells and marginal zone B (MZB) cells presenting α-GC in vitro, but both cytokines were produced when DC were added. Two other studies demonstrated weak Th2 (IL-4 and IL-13) production by murine iNKT cells after stimulation with α-GC–pulsed total B cells (52) or MZB cells (53) in vitro and in vivo, and these cytokine profiles were skewed toward Th1 when DC were present. We found that when α-GC–pulsed human B cells were cultured with CD4^{+} or DN iNKT cells, but not CD8^{+} iNKT cells, IFN-γ, TNF-α, IL-4, IL-5, and IL-13 were secreted into the supernatants. Using intracellular cytokine staining and flow cytometry, we showed that iNKT cells are the main source of these cytokines. However, the amounts of cytokines released were 10–1000-fold lower than those when DC were used as APC for α-GC. Glycolipid presentation by B cells appears to be required for optimal activation of iNKT cells by DC, because removal of MZB cells reduced iNKT cell activation by murine spleen cells pulsed with α-GC in vitro (51), and human PBMC depleted of B cells failed to support iNKT cell expansion and cytokine release in response to α-GC (44). In contrast, Bezbradica and coworkers (52) reported that B cells suppressed murine DC-mediated iNKT cell activation in vivo. Collectively, these findings support the view that B cells can present glycolipid Ags to iNKT cells, but rather than being potent stimulators of cytokine secretion, B cells modulate cytokine production by iNKT cells activated by DC. Reciprocally, iNKT cells can induce cytokine production by DC (7, 8, 32) and by small proportions of B cells.

Because CD8^{+} and DN iNKT cells and, to a lesser degree, CD4^{+} iNKT cells are potent cytotoxic T cells capable of killing CD1d^{+} cells presenting α-GC (13), we investigated if these iNKT cell subsets could kill autologous B cells presenting this glycolipid. Interestingly, only the DN subset of iNKT cells degranulated in response to B cells, and this occurred whether α-GC was present or not. Thus, although iNKT cells can promote Ab production by B cells, DN iNKT cells may regulate this activity by killing the B cells.

iNKT cells can induce maturation of DC into APC that express costimulatory and adhesion molecules and can prime naive conventional T cells (7, 8, 32). B cells are also professional APCs (30), and they express CD1d; therefore, we investigated the influence that iNKT cells and their subsets have on the APC function of B cells. Extending the findings of Kitamura and coworkers (54), we found that iNKT cells induced the expression of CD40, CD69, CD83, and CD86, but not CD80 nor HLA-DR, on B cells by a mechanism that was dependent on cell–cell contact and CD1d. Of the three iNKT cell subsets, CD4^{+} iNKT cells were the most potent inducers of costimulatory molecule expression by B cells. Blocking IL-13 resulted in moderate inhibition of CD86 expression, but blocking IL-4 had no effect on the expression of these markers by B cells. These phenotypic changes suggest that iNKT cells induce maturation of B cells into APCs. We found that B cells presented Ags, superantigens, and mitogens to T cells resulting in their proliferation. However, B cells that were precultured with iNKT cells were greatly reduced in their ability to induce T cell proliferation. Nonspecific and PPD-stimulated T cell proliferation was abrogated by iNKT cells, whereas SEB-specific T cell proliferation was not. As SEB does not require intracellular processing to be presented on MHC, our results suggest that iNKT cells may inhibit intracellular Ag processing by B cells. Allogeneic T cell proliferation was also abrogated by iNKT cells. This inhibition of B cell–stimulated T cell proliferation occurred whether or not α-GC was present in the iNKT–B cell cocultures. These data are consistent with a model in which iNKT induce the differentiation of B cells into tolerogenic APC that inhibit conventional T cell activation. Subsets of B cells that are tolerogenic APCs have been described (55, 56), and although not shown in this study, it is possible that the induction of T cell proliferation by B cells may be inhibited by CD1d^{hi}CD5^{+} Breg cells or by IL-10 released by other B cells.

CD4^{+} T cell help for B cells is a key requirement for the generation of Ab-secreting plasma cells and memory B cells. The interaction between the two cells generally takes place in secondary lymphoid organs, involves presentation of processed Ag by the B cell to the T cell, signaling through costimulatory molecules such as CD40, and the production of cytokines (1–3). Our study demonstrates that human B cells can present glycolipid Ag to iNKT cells, resulting in low-level Th1 and Th2 cytokine secretion in vitro. Reciprocally, iNKT cells can have diverse effects on B cells, depending on the iNKT cell subset, on whether glycolipid Ag is added and possibly on the differentiation status of the B cell. Firstly, CD4^{+}, CD8^{+}, and DN iNKT cells can all stimulate Ab production by B cells by a mechanism that requires CD1d but not exogenous glycolipid Ag nor CD40–CD154 interaction. Secondly, CD4^{+} iNKT cells in the presence of glycolipid Ag promote differentiation of naive B cells into memory cells, but they do not appear to promote Ig isotype switching by these cells. Thirdly, CD4^{+} iNKT cells in the absence of exogenous glycolipid Ag induce the expansions of B cells that exhibit phenotypes of Breg cells and B cells that produce IL-10, whereas DN iNKT cells in the absence of added glycolipid may kill autologous B cells. Finally, iNKT cells (and in particular the CD4^{+} subset) induce maturation of all B cell subsets into cells with APC phenotypes, but these APCs fail to stimulate proliferation of conventional T cells, as seen when untreated B cells are used. Collectively, these results indicate that the presence of exogenous α-GC is a major determinant of the outcome of B–iNKT cell interactions: in the presence of α-GC, B cells promote cytokine secretion by iNKT cells, which will boost T cell–mediated immunity, whereas in the absence of α-GC, iNKT cell activation by B cells results in Ab-mediated immune responses and suppression of T cell–mediated immunity. The dependence of these functional outcomes on the absence or presence of α-GC raises the question of how other glycolipid Ags will modify B cell responses to iNKT cells, and in this regard, several chemical analogs of α-GC that can skew cytokine responses of iNKT cells are being tested as potential immunomodulators for the treatment of disease (32, 57, 58). The diverse outcomes of iNKT–B cell interactions have important implications for therapy for autoimmune disease, in which induction of Breg cells or prevention of pathogenic Ab responses may be beneficial (34, 35, 45, 46, 48–50), and for cancer and infectious disease, in which T cell responses are required (4, 5). The presence of iNKT cell subsets with opposing roles in immune responses might explain why clinical trials involving these cells to date have been unsuccessful (38, 39). Therapeutic manipulation of iNKT cells may necessarily require the sorting of iNKT cells into functionally-distinct subsets and/or selective activation of particular effector functions using customized glycolipid Ags.

Disclosures

M.A.E. has an equity relationship with NKT Therapeutics, Inc. The other authors have no financial conflicts of interest.

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