Immunoregulatory Role of CD1d in the Hydrocarbon Oil-Induced Model of Lupus Nephritis


J Immunol 2003; 171:2142-2153; doi: 10.4049/jimmunol.171.4.2142
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Immunoregulatory Role of CD1d in the Hydrocarbon Oil-Induced Model of Lupus Nephritis


Systemic lupus erythematosus (SLE, lupus) is a systemic autoimmune disease that is accompanied by the emergence of autoreactive T cells and a reduction in regulatory T cells. Humans and mice with SLE have reduced numbers of CD1d-restricted NK T cells, suggesting a role for these cells in the regulation of SLE. In this study, we show that CD1d deficiency exacerbates lupus nephritis induced by the hydrocarbon oil pristane. This exacerbation in disease is associated with: 1) reduced TNF-α and IL-4 production by T cells, especially during the disease induction phase; and 2) expansion of marginal zone B cells. Strikingly, inoculation of pristane in wild-type mice resulted in reduced numbers and/or functions of NK T cells and CD1d-expressing dendritic cells. These findings suggest that CD1d may play an immunoregulatory role in the development of lupus in the pristane-induced model. The Journal of Immunology, 2003, 171: 2142–2153.

Received for publication November 15, 2002. Accepted for publication June 17, 2003.

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1 This work was supported in part by grants from the National Institute of Health (AR47322 to R.R.S., AI44074 to W.H.R., HL68744 and AI50953 to L.V.K., and HL32610; ‡ Department of Medicine, University of Florida, Gainesville, FL) and by Cancer Research U.K. Program Grant C3999/A2291 (to V.C.).
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5 Abbreviations used in this paper: SLE, systemic lupus erythematosus; α-GalCer, α-galactosylceramide; DC, dendritic cell; KBS, kidney biopsy score; GAS, glomerular activity score; TIAS, tubulointerstitial activity score; BUN, blood urea nitrogen; CLS, chronic lesions score.

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The Journal of Immunology

Morine NK T cells coexpress CD1 marker cells (e.g., CD161) and T cell markers (i.e., invariant TCR Vα14Jα8 chains paired predominantly with Vβ8 chains), are mostly CD4+ or double negative, and are specific for the MHC class I-like molecule CD1d (12). CD1d molecules present a yet unknown ligand, mimicked by the glycolipid α-galactosylceramide (α-GalCer), to NK T cells (12–15). CD1d-reactive NK T cells, which can be tracked using CD1d/α-GalCer tetramers (16–18), appear to play protective roles against a variety of immune-mediated conditions including autoimmune diabetes (19–21).

NZB/NZW F1 and MRL-lpr/lpr mice that spontaneously develop autoimmune diseases and nephritis have served as useful models to study the pathogenesis of SLE (2–4, 7, 22). Recent introduction of induced models of lupus, generated in otherwise normal mouse strains by exposure to hydrocarbon oils such as pristane, has further facilitated investigations into SLE (23, 24). Mechanisms by which pristane induces lupus-like autoimmunity are poorly understood.

To address the role of CD1d in the pathogenesis of lupus, we have crossed a CD1d-null genotype (CD1d−/−) onto the BALB/c background and have investigated the effect of CD1d deletion on the development of nephritis, autoantibody production, and cytokine responses in the pristane-induced model. We have also examined the effects of pristane inoculation in wild-type BALB/c mice on the numbers and/or functions of NK T cells, CD1d-expressing dendritic cells (DCs), and marginal zone B cells. Our results indicate that CD1d deficiency exacerbates pristane-induced lupus and that pristane inoculation in CD1d-sufficient mice suppresses the numbers and/or functions of CD1d-expressing DCs and NK T cells and enhances the numbers of marginal zone B cells. These findings suggest an immunoregulatory role of CD1d in lupus.

Materials and Methods

Mice

CD1d−/− 129 × C57BL/6 mice (25) were crossed onto the BALB/cJ background (The Jackson Laboratory, Bar Harbor, ME) for nine generations. At each backcross, heterozygous (CD1d−/+) mice were identified by Southern
Nunc, Naperville, IL) were coated with 50 by reversed-phase HPLC. Microtiter plate wells (Maxisorp Immunoplate; normal) were preincubated to establish CD1d+/BALB/c mice. The CD1d+ phenotype was further confirmed by flow cytometry of PBLs stained with a conjugated anti-CD1 mAb, 1B1 (BD Pharmingen, San Diego, CA). Anti-DNA Ab were measured by ELISA, as previously described (6, 7). Anti-DNA Ab titers are expressed as units per milliliter using a reference-positive standard of pooled serum from MRL-lpr/lpr mice.

**Flow cytometry**

For liver NKT cells, liver was perfused with PBS via the portal vein until opaque and pressed through a 70-μm cell strainer (BD Biosciences, Mountain View, CA). Hepatocytes were pelleted by centrifugation at 30 × g for 3 min. The remaining liver cells in the supernatant were pelleted at 300 × g for 5 min and then resuspended in a 40% isotonic Percoll solution (Amersham Pharmacia Biotech, Piscataway, NJ). This suspension was underlaid with a 60% isotonic Percoll solution. After centrifugation for 20 min at 1500 × g, mononuclear cells were isolated at the 40%/60% interface, and then washed once with RPMI 1640 medium (Life Technologies, Grand Island, NY) with 5% FCS (HyClone Laboratories, Logan, UT). The cells were stained with murine CD1d/or-Galectin tetratetramers that were generated as described elsewhere (18) or with human CD1d/or-Galectin tetramers that also recognize murine NKT cells (17). Stained cells were analyzed by flow cytometry. Spleen or thymus cells were incubated with anti-CD16/32 (2.4G2; BD Pharmingen) to block FcγRIII/IIa, followed by staining with various conjugated mAbs (all BD Pharmingen), as indicated in the figure legends. Stained cells were analyzed using a BD Biosciences FACSCalibur flow cytometer and CellQuest software.

**Activation of NKT and T cells**

For in vitro NKT cell activation, spleen cells (1–2 × 10^6/ml) were incubated with titrated doses of synthetic α-Galectin (KRN7000; Kirin Brewery, Gunma, Japan) (15). For T cell activation, splenocytes (2 × 10^5/well) were stimulated with plate-bound anti-CD3 mAb (1–10 μg/ml) and supernatants were collected after 48 h of culture for the measurement of cytokines.

**Detection of cytokines**

A standard sandwich ELISA was used to measure cytokines (Figs. 3 and 5a), as previously described (4). TNF-α levels were measured using the BD Pharmingen mouse cytokine cytometric bead assay kit (Fig. 4) according to the manufacturer’s instructions. To examine the cellular sources of cytokines in α-Galectin-stimulated cultures (Fig. 5, b–e), a cytokine secretion assay was performed using the MACS cytokine secretion assay kit (Miltenyi Biotec, Auburn, CA) according to the manufacturer’s protocol with some modifications. Briefly, stimulated or control spleen cells (1 × 10^7) were incubated at 37°C for 45 min with the cytokine Catch Reagent, which attaches to all leukocytes via CD45 Ag and binds to the specific cytokine. After washing, cells were stained with PE-conjugated cytokine detection Ab, followed by incubation with anti-PE microbeads. Cytokine-secreting cells were then positively selected using AutoMACS (Miltenyi Biotec). Cytokine-enriched cells were counterstained with DX5, CD1d/or-Galectin tetratetramer, and TCRβ and analyzed by flow cytometry. Dead cells and B cells, which can nonspecifically bind to cytokine detection Ab via PE, were excluded by staining with propidium iodide and PerCP-conjugated B220 (BD Pharmingen), respectively.

**Statistical analysis**

Levels of Abs and cytokines, lymphocyte percent and numbers, and renal scores were compared using Student’s t or Mann-Whitney U test. Frequencies of Abs, proteinuria, and BUN were compared using the two-sided Fisher’s exact test.

**Results**

CD1d deficiency accelerates pristane-induced lupus nephritis

Inoculation of hydrocarbon oils such as pristane induces lupus-like autoantibody production and mild glomerulonephritis in otherwise normal mouse strains such as BALB/c (Refs. 23 and 24, and see data in CD1d+ mice in Figs. 1 and 2). To determine whether CD1d is involved in the development of pristane-induced lupus, we backcrossed CD1d+ 129/B6 mice onto the BALB/c background for nine generations and inoculated the final CD1d+ and control BALB/c mice with pristane or PBS. All mice were bled before and at 3 and 6 mo postinoculation and monitored for proteinuria.

Proteinuria developed early and was more severe in the pristane-inoculated CD1d+ mice than in the CD1d+ littermates (Fig. 1a). At 6 mo postinoculation, 54% of the mice in the CD1d+, but none in

**Renal histochemistry**

Paraffin sections of kidneys fixed in 4% paraformaldehyde were stained with H&E, periodic acid-Schiff, and Masson’s trichrome. Stained sections were scored for the following features on a 0–3 scale by three of us (R.R.S., J.-Q.Y., S.R.K.) in a blind fashion, as described previously (22): 1) Glomerular activity score (GAS) that included glomerular proliferation, karyorrhexis, fibrinoid necrosis, cellular crescents, inflammatory cells, and hyaline deposits; 2) tubulointerstitial activity score (TIS) that included interstitial inflammation, tubular cell pyknosis, nuclear activation, cell necrosis and cell flattening, and epithelial cells or macrophages in tubular lumens; 3) chronic lesions score (CLS) that included glomerular scars, glomerulocapsular, fibrous crescents, tubular atrophy, and interstitial fibrosis; and 4) vascular lesion score that included arterial/arteriolar lesions.

The raw scores assigned by various readers were averaged to obtain a mean score for each of the individual features. The mean scores for individual features were summed to obtain the four main scores (GAS, TIS, CLS, and vascular lesion score) and then all four scores were summed to determine a composite kidney biopsy score (KBS).

**Renal immunostaining**

Frozen kidney sections were fixed with methanol and acetone (1:1) for 5 min. Slides were washed and incubated with biotinylated rat anti-mouse-Thy1.2, -CD4, -CD8, -CD11b and -B220 mAbs or control rat IgG (BD Pharmingen). Sections were then stained using Vectastain ABC-AP kit and Vector red alkaline phosphatase substrate kit I (Vector Laboratories, Burlingame, CA) followed by the manufacturer’s instructions. For immunofluorescence, sections were stained with FITC-conjugated goat anti-mouse IgG (Sigma-Aldrich). Slides were read by three of us in a blind fashion.

**Autoantibodies against nuclear and cytoplasmic Ags**

Abs against cellular proteins were analyzed by immunoprecipitation of 35S-radiolabeled K562 cell extract using 4 μl of serum/sample (23). Specificity was confirmed using reference sera containing anti-nRNP, Sm, Su, or ribosomal P Abs. For anti-ribosomal P peptide ELISA, a carboxyl-terminal 22-aa peptide carrying the major epitope of ribosomal P O recognized by human and murine autoimmune sera was synthesized by F-moc chemistry using a Rainin Synthesis/Multiplex peptide synthesizer and purified by reversed-phase HPLC. Microritre plate wells (Maxisorp Immunoplate; Nunc, Naperville, IL) were coated with 50 μl of peptide (2 μg/ml) in 20 mM Tris-HCl (pH 8) at 4°C for 16 h. The wells were washed once with NET/Nonidet P-40 (150 mM NaCl, 2 mM EDTA, 20 mM Tris (pH 7.5), and 0.3% Nonidet P-40) and blocked with 0.5% BSA in NET/Nonidet P-40 for 1 h at 22°C. They were then incubated with 100 μl of 1/500 mouse serum in blocking buffer for 2 h. Wells were washed, incubated with 100 μl of 1/1000 alkaline phosphatase-conjugated goat anti-mouse IgG (Southern Biotechnology Associates, Birmingham, AL) for 2 h. Plates were developed with p-nitrophenyl phosphate substrate and OD was determined at 405 nm using an ELISA plate reader ( Molecular Devices, Menlo Park, CA).
the CD1d⁺ group, had ≥100 mg/dl (moderate to severe) proteinuria \( (p < 0.0001) \). The frequency of moderate to severe proteinuria was still high in CD1d⁺ mice at 10 mo (75% in CD1d⁺ vs 16% in CD1d⁻; \( p = 0.005 \)). None of CD1d⁺, but 63% of CD1d⁻, mice developed severe (≥300 mg/dl) proteinuria at 10 mo postinoculation \( (p = 0.0001) \).

BUN was also elevated in pristane-inoculated CD1d⁺ mice (Fig. 1b), suggesting an advanced renal disease in these mice. Nine (82%) of 11 CD1d⁺, but 0 of 7 CD1d⁻, mice had elevated (>15 mg/dl) BUN \( (p = 0.002) \). Two (18%) of 11 CD1d⁺ mice had a severely elevated BUN (≥30 mg/dl).

Mice were sacrificed at 10 mo of age to harvest kidneys and their renal histology was analyzed (Fig. 1, c and d). Mild and focal mesangial proliferative glomerulonephritis was found in 60% of pristane-inoculated CD1d⁺ mice (Fig. 1d, middle panels), the remaining 40% of mice had no evidence of nephritis by light microscopy, and none of the CD1d⁺ mice had diffuse proliferative or chronic lesions. CD1d⁺ mice, however, developed diffuse proliferative glomerulonephritis with fibrous crescents, glomerulosclerosis, tubular atrophy, and interstitial fibrosis in 50% of mice (Fig. 1d, right panels); another 25% of pristane-inoculated CD1d⁺ mice had mild to moderate mesangio proliferative lesions; and the remaining 25% of mice had...
mild focal or no lesions. A composite KBS (see Materials and Methods) was increased in pristane-inoculated CD1d<sup>−/−</sup> mice (p < 0.05). Further analysis of the KBS revealed an increase in active (GAS) as well as chronic kidney lesions (CLS) in CD1d<sup>−/−</sup> mice (Fig. 1c). None of the PBS-injected mice (six CD1d<sup>−/−</sup>, five CD1d<sup>+/+</sup>) had proteinuria or renal histological changes (Fig. 1d, left panels).

As shown in Fig. 1d, inflammatory cell infiltration was increased in CD1d<sup>−/−</sup> mice. To determine the phenotype of kidney-infiltrating cells, kidney sections were stained with conjugated anti-Thy1.2, anti-CD4, anti-CD8, anti-CD11b, and anti-B220 Abs. Infiltrating cells that were mostly T cells and macrophages were increased in CD1d<sup>−/−</sup> mice as compared with CD1d<sup>+/+</sup> mice (Fig. 1e). B220<sup>−</sup> cells were rarely detected in kidney sections from both groups of animals (data not shown).

**CD1d deficiency enhances pristane-induced autoantibody production**

Pristane-inoculated BALB/c mice develop autoantibodies to several cellular Ags (23, 24). We detected these Abs with an immunoprecipitation assay using cell extract from an erythroleukemia cell line, K562, as a source of autoantigens. Overall, reactivity to cellular Ags was higher in sera from pristane-inoculated CD1d<sup>−/−</sup> mice than in sera from pristane-inoculated CD1d<sup>+/+</sup> or PBS-injected CD1d<sup>−/−</sup> or CD1d<sup>+/+</sup> mice (Fig. 2a). Anti-ribosomal P (Fig. 2a) and anti-OJ (isoleucyl tRNA synthetase complex) Abs (Fig. 2b), which are generally not induced in pristane-inoculated wild-type BALB/c mice (23, 24, 26), were detected in 3 (13%) of 23 CD1d<sup>−/−</sup> mice, but in none of 16 CD1d<sup>+/+</sup> mice. Levels of some of these autoantibodies were quantitated by ELISA. As shown in Fig. 2c (left panel), anti-ribosomal P peptide Abs were significantly increased in the CD1d<sup>−/−</sup> mice as compared with wild-type littermates (p < 0.01). Serum IgG anti-dsDNA Ab levels, as measured by ELISA, were also higher in CD1d<sup>−/−</sup> than in CD1d<sup>+/+</sup> mice at 6 mo postinoculation (p < 0.05; Fig. 2c).

**T cell cytokine responses in pristane-injected CD1d-deficient BALB/c mice**

Abnormalities in cytokine production contribute to the development of lupus (24). To determine whether exacerbation of lupus in CD1d<sup>−/−</sup> animals is related to abnormalities in cytokine production, we measured cytokine responses in the spleens of pristane-inoculated CD1d<sup>−/−</sup> and CD1d<sup>+/+</sup> BALB/c mice. After 12–24 h, 10–12 days, 6 wk, and 6 mo of pristane inoculation, spleen cells were...
stimulated in vitro with α-GalCer, anti-CD3 Ab, or Con A (Figs. 3 and 4 and data not shown). As expected, CD1d\(^{-}\) mice exhibited no cytokine response to α-GalCer stimulation. Upon stimulation with anti-CD3 (Fig. 3) or Con A (data not shown), IL-4 levels were significantly decreased, whereas IFN-γ and IL-2 levels were unchanged in CD1d\(^{+}\) mice as compared with CD1d\(^{-}\) mice; there was no difference in the levels of these cytokines between PBS vs pristane-inoculated mice at 12 h and 11 days after pristane inoculation. This change in cytokine profile in CD1d\(^{-}\) mice was not associated with significant alterations in various spleen cell populations, including CD4, CD8, DC, B220, macrophages, and neutrophils (Ref. 25 and data not shown). At 6 mo, IL-4 and IL-13 production was lower in pristane-inoculated than in PBS-injected animals (Fig. 4). Such selective deficiency in T cell production of TNF-α during the initial phases of disease development may contribute to the development and exacerbation of disease in wild-type and CD1d\(^{-}\) mice, respectively.

Results of TNF-α production by T cells revealed a striking pattern (Fig. 4). TNF-α levels, upon Con A or anti-CD3 stimulation, were similar between PBS-injected CD1d\(^{+}\) and CD1d\(^{-}\) mice. In pristane-inoculated mice, however, TNF-α levels in Con A or anti-CD3-stimulated cultures significantly decreased on days 10–12 postinoculation (\(p < 0.05\)), regardless of the CD1d status of the mouse. At 6 mo postinoculation, TNF-α levels were slightly increased in pristane-inoculated mice (\(p = \text{NS}\)). Such selective deficiency in T cell production of TNF-α during the initial phases of disease development may contribute to the development and exacerbation of disease in wild-type and CD1d\(^{-}\) mice, respectively.

**NKT cell functions and numbers are reduced in pristane-injected animals**

Although the lack of cytokine production upon α-GalCer stimulation was expected in CD1d\(^{+}\) mice, it was surprising that in wild-type mice α-GalCer-induced TNF-α production was significantly lower in pristane-inoculated than in PBS-injected animals (Fig. 4). This suggested that pristane inoculation itself alters NKT cell functions. To further evaluate the effect of pristane on NKT cell functions, spleen cells were harvested from BALB/c mice at various time points (12–24 h, 10–12 days, 6 wk, and 6 mo) after pristane or PBS injection and stimulated with α-GalCer for 40–48 h. Culture supernatants were assayed for various cytokines, which were significantly decreased in the pristane group at 10–12 days (\(p < \text{NS}\)).

**FIGURE 3.** Effect of CD1d deficiency on T cell cytokine production in the pristane-induced lupus model. PBS- or pristane-injected CD1d\(^{+}\) or CD1d\(^{-}\) mice were sacrificed at 12–24 h, 11 days, or 6 mo after pristane inoculation. Their spleen cells were stimulated with anti-CD3 for 48 h and culture supernatants were tested for cytokines. *\(p < 0.05\) to \(< 0.0001\), \(n = 3–7\) mice/group.

**FIGURE 4.** T cell production of TNF-α is selectively decreased during the initial phases of development of pristane-induced lupus. Ten- to 14-wk-old CD1d\(^{+}\) and CD1d\(^{-}\) BALB/c mice were injected with PBS or pristane (\(n = 3–5\) mice/group). Their spleen cells were cultured with medium alone, α-GalCer, Con A, or anti-CD3 Ab. TNF-α levels were measured in culture supernatants. Note that PBS-injected CD1d\(^{+}\) mice had no TNF-α response to α-GalCer, but had normal TNF-α response when their spleen cells were stimulated with anti-CD3 or Con A. Pristane-injected CD1d\(^{-}\) mice, however, had decreased TNF-α response to α-GalCer stimulation at all times tested (\(p < 0.01\), pristane- vs PBS-injected CD1d\(^{+}\) mice). TNF-α response to Con A or anti-CD3 stimulation was decreased on days 10 and 11 (\(*, p < 0.05\), pristane- vs PBS-injected CD1d\(^{+}\) or CD1d\(^{-}\) mice), but not at 12–20 h or 6 mo time points. Results shown are from one of two similar experiments.
We then assessed the effect of pristane on in vivo NKT cell functions. Mice were injected with pristane or PBS and 12–24 h, 10–11 days, or 6 mo later injected i.v. with 4 µg α-GalCer and bled 2 h later for detection of cytokines in serum samples (Fig. 5).
right panel). All cytokines tested were markedly reduced at 6 mo postinoculation (p = 0.002–0.00003, pristane vs PBS-injected mice). Serum IL-2 and IL-13 levels decreased as early as 12–24 h after pristane inoculation, while serum levels of other cytokines were variable at 12 h and 10 days postinoculation. Thus, NKT cell cytokine responses, as assessed by brief in vivo or in vitro exposure to α-GalCer, markedly decline after pristane inoculation.

α-GalCer-induced responses shown in Fig. 5a may reflect its direct effect on NKT cells as well as the secondary effects of NKT cell activation on other immune cells (27). To investigate this further, PBS- or pristane-inoculated mice were injected i.v. with 4 µg α-GalCer. Two hours later, mice were sacrificed and their spleen cells were enumerated for cytokine-secreting CD1d/α-GalCer tetramer+ cells using a cytokine secretion assay. Less than 2% of live B220+ lymphocytes in α-GalCer-primed (Fig. 5b) and few cells in unprimed (Fig. 5e) animals were positive for IFN-γ, IL-2, or IL-4. Most cytokine+ cells were tetramer positive (Fig. 5b). To further confirm this, spleen cells (1 × 10^7) were enriched for cytokine+ cells (Fig. 5c), which was highly efficient (>98.5%) for all three cytokines tested. Among all IFN-γ+ cells in PBS-injected mice, 88% were NKT cells (TCRβ+ tetramer+) and ~6% each were conventional T cells (TCRβ+ tetramer-) or NK cells (TCRβ+DX5+) (Fig. 5d). Only a few cytokine-secreting tetramer+ cells expressed DX5 (Fig. 5d). Intriguingly, IL-4-secreting cells expressed more DX-5 than IL-2 or IFN-γ-secreting NKT cells (Fig. 5d). Gadue and Stein (28) made a similar observation that more DX5+ thymic NKT (tetramer+) cells secrete IL-4 than DX5+ thymic NKT cells. Thus, most IFN-γ-, IL-2-, or IL-4-secreting cells after brief in vivo α-GalCer exposure are NKT cells. The percent (Fig. 5b) and numbers (Fig. 5c) of these cells were lower in pristane-inoculated mice than in PBS-injected mice. Interestingly, the remaining NKT cells in pristane-injected mice had a Th1 phenotype, i.e., decreased IL-4 and increased IFN-γ expression as compared with NKT cells from PBS-injected mice (Fig. 5f): The mean fluorescence intensities on tetramer+ cells were 157 vs 202 for IL-4 and 220 vs 194 for IFN-γ in pristane- vs PBS-injected mice, respectively.

α-GalCer stimulation induces the expression of activation markers on spleen cells (27). To assess whether this function of NKT cells is also compromised in pristane-induced lupus, α-GalCer-stimulated spleen cells from PBS- or pristane-inoculated wild-type and CD1d+ mice were analyzed for activation and memory markers, CD25, CD44, CD62 ligand, CD69, CD80, and CD86, by flow cytometry (Fig. 6 and data not shown). Significant decreases in the induction of CD25 and CD69 on B and T cells were observed at 6 mo postinoculation (p = 0.03–0.0005; Fig. 6), but not significantly at earlier time points, i.e., 12 h and 10–12 days postinoculation (data not shown). On CD1d+/α-GalCer tetramer+ cells, however, decreases in CD25 and CD69 expression were observed as

Figure 6. α-GalCer-induced expression of activation markers on spleen cells is reduced in pristane-inoculated mice. Six months after pristane inoculation, mice were injected with 4 µg of α-GalCer i.v., their spleens were harvested 2 h later, and the spleen cells were cultured with α-GalCer for 40 h. Expression of activation markers, CD25, CD44, CD69, CD86, and CD62 ligand, on B and/or T cells is shown. The (mean ± SE) percentage of cells expressing these markers is shown in the table. *, p < 0.05 and **, p < 0.01 compared with PBS-injected wild-type mice (WT/PBS/α-GC group); n = 3–5 mice/group. Similar levels of the expression of activation markers were observed in CD1d+ mice injected with α-GalCer and wild-type mice injected and cultured with vehicle alone (WT/PBS/Vehicle group). Results are from one representative of three independent experiments.
early as 10 days postinoculation. For example, the percent CD69+ tetramer+ cells (6.6 ± 0.6 vs 12 ± 1% of gated TCRβ+ cells, p < 0.05) as well as the mean fluorescence intensity of CD69 on tetramer+ cells (51 ± 2.3 vs 63 ± 5.7, p < 0.05) were significantly reduced in pristane-inoculated as compared with PBS-injected mice. Pristane inoculation also affected the induction of other activation and memory markers. For example, the induction of CD44 and CD86 expression was significantly lower in pristane-injected than in control animals. A minor effect of CD44 and CD86 expression was significant in lupus mice. To examine such a possibility, we analyzed CD4 and CD8 expression on tetramer+ cells at 6–8 wk after pristane injection (Fig. 7b). In the thymus, the reduction in percent and total tetramer+ cells in pristane-injected animals was seen in all three subsets, CD4+, CD4–CD8+, and CD4–CD8– double-positive cells. In the spleen, the percent, but not total, CD4+ and CD4–CD8– tetramer+ cells were reduced in pristane-inoculated mice (p < 0.05). Thus, all subsets of invariant NKT cells decline in pristane-injected animals.

NKT cells comprise diverse phenotypes of T cells (19); some subsets that may contribute to immune regulation and protection against autoimmunity might be particularly deficient in lupus mice. To examine such a possibility, we analyzed CD4 and CD8 expression on tetramer+ cells at 6–8 wk after pristane injection (Fig. 7b). In the thymus, the reduction in percent and total tetramer+ cells in pristane-injected animals was seen in all three subsets, CD4+, CD4–CD8+, and CD4–CD8– double-positive cells. In the spleen, the percent, but not total, CD4+ and CD4–CD8– tetramer+ cells were reduced in pristane-inoculated mice (p < 0.05). Thus, all subsets of invariant NKT cells decline in pristane-injected animals.

Thus, primary NKT cell functions as well as secondary effects of NKT cells on other immune cells are markedly compromised in pristane-inoculated BALB/c mice. Although a significant decrease in NKT cell numbers and most NKT cell functions are detectable 6 wk after pristane inoculation, some impairment of NKT cell functions, such as TNF-α and IL-2 production upon α-GalCer stimulation, begins as early as 12–24 h after pristane exposure.

To explore the mechanisms of decline in NKT cell functions and numbers after pristane inoculation, we examined the effect of pristane inoculation on CD1d-expressing APC (Fig. 8). Overall, the expression of CD1d was decreased in spleen cells of pristane-inoculated mice as compared with untreated control animals (mean fluorescence intensity, 79 ± 0.8 vs 98 ± 3.6, p < 0.05). Specifically, the number of CD1d-expressing CD11c+ DCs was significantly decreased in pristane-inoculated mice as compared with control animals (6.7 ± 0.2 vs 9.4 ± 0.3, p < 0.01). The CD1d+ CD11c+ DCs could be subdivided into three subsets, namely, CD1d+CD11c+CD11c bright, CD1d+CD11c+CD11c low, and CD1d+CD11c+CD11c bright cells. Significant differences between the pristane-inoculated and control mice were seen in the numbers of CD1d+CD11c+CD11c bright (1.7 ± 0.2 vs 25 ± 0.3, p < 0.05) and CD1d+CD11c+CD11c low subsets (3.3 ± 0.3 vs 5.2 ± 0.1, p = 0.02) of CD11c+ cells. The CD1d-expressing B220+ cells were also slightly decreased in pristane-inoculated mice (p = 0.04–0.06). There was no significant effect of pristane injection on the numbers of CD1d-expressing macrophages (CD11b+1 and T cells. Thus, pristane inoculation results in decreased numbers of CD1d-expressing DCs and B

FIGURE 7. Decreased NKT cell numbers in pristane-inoculated mice. Eight weeks after inoculation with pristane or PBS, 16-wk-old BALB/c mice were sacrificed and their thymus and spleen cells were analyzed for CD1d/α-GalCer tetramer+ cells. a, TCRβ+ tetramer+ cells are expressed as the mean ± SE (percent) of gated lymphocytes or as the absolute numbers × 10⁶. b, NKT cell subsets (CD4+ tetramer+, CD4+CD8+ tetramer+, and CD4+CD8– tetramer+ cells) are expressed as the mean percentage of gated lymphocytes. Note that TCRβ+ tetramer+ thymocytes (a) and both CD4+ and CD4– subsets of tetramer+ thymocytes or splenocytes (b) were significantly lower in pristane-injected than in control animals. A minor population of double-positive (CD4+CD8+) tetramer+ thymocytes was also decreased in pristane-injected mice as compared with control mice (b) *p < 0.05; **p < 0.01, n = 3–6 mice/group, ±SE. Results are representative of three independent experiments.

FIGURE 8. Reduced numbers of CD1d-expressing DCs in pristane-inoculated mice. Twelve days after inoculating with pristane or PBS, BALB/c mice were injected i.v. with 4 μg of α-GalCer and sacrificed 2 h later. Total spleen cell numbers were similar between the two groups of animals. CD1d+ CD11c+, CD1d+ B220+, CD1d+ CD11b+, and CD1d+ TCRβ+ cells are expressed as the mean percentage of spleen cells. *p < 0.01, n = 5 mice/group. Results are representative of three independent experiments.
cells, which, in turn, may be responsible for the decreased NKT cell functions in pristane-induced lupus.

**Effect of CD1d deficiency on marginal zone B cells in pristane-inoculated BALB/c mice**

Results in Fig. 8 show that, while overall CD1d expression was decreased on B cells, the CD1d<sup>high</sup>B220<sup>+</sup> cells that correspond to marginal zone B cells (29) were increased in pristane-injected mice in two separate experiments (total number of cells ($\times 10^6$)) were $3.7 \pm 0.7$ and $8.1 \pm 0.9$ in PBS- vs pristane-injected mice, $p < 0.05$). To further examine the effect of pristane inoculation and CD1d deficiency on marginal zone B cells, we enumerated CD21<sup>high</sup>CD23<sup>low</sup> B cells in the spleens of CD1d<sup>+</sup> and CD1d<sup>o</sup> mice on day 11 or 30 (Fig. 9, a and b) or at 6 or 12 mo (data not shown) after pristane or PBS injection. We found that marginal zone B cells were increased by ~1.5- to 2-fold in the pristane status of mice. Interestingly, this expansion of marginal zone B cells was restored to normal in pristane-injected BALB/c mice treated with a CD1d ligand, α-GalCer (A. K. Stanic, J.-Q. Yang, L. V. Kaer, and R. R. Singh, manuscript in preparation). Additionally, although serum IgG1 and IgG2a levels were similar between the two groups of animals (data not shown), serum levels of IgG3 isotype that is known to be preferentially secreted by marginal zone B cells (29) were significantly higher in pristane-injected CD1d<sup>+</sup> mice than in pristane-injected CD1d<sup>o</sup> mice (Fig. 9c). Previous studies have reported reduced CD23 expression on B cells in lupus-prone NZB mice (30). We found that the mean fluorescent intensity of CD23 expression on B cells was also reduced in pristane-injected mice as compared with PBS-injected mice, regardless of the CD1d status of mice, although the differences were not statistically significant (data not shown).

**Effect of α-GalCer-activated NKT cells on autoantibody production in vitro**

Our findings suggest that the development of lupus-like disease in pristane-inoculated wild-type mice and its exacerbation in CD1d<sup>+</sup> animals is related, at least in part, to the induced or genetic deficiency of NKT cells, respectively. To provide further support for this possibility, we tested whether NKT cell activation can suppress autoantibody production by B cells from pristane-injected mice. For this purpose, B cells isolated from the spleens of pristane-inoculated BALB/c mice were cocultured with T cells isolated from the spleens of PBS-injected control animals, with or without α-GalCer. Supernatants collected on day 6 were tested for IgG anti-DNA Ab and rheumatoid factor. IgG anti-DNA Ab, and rheumatoid factor levels in these cultures were generally low and were not affected by the addition of α-GalCer (data not shown). However, in LPS-stimulated cultures, which had high levels of rheumatoid factor, addition of α-GalCer significantly decreased rheumatoid factor levels (Fig. 10).

**Discussion**

In this article, we report that lupus nephritis, which is generally mild in pristane-inoculated BALB/cJ mice, is quite severe and advanced in CD1d<sup>+</sup> mice. Anti-ribosomal P and anti-OJ Abs that are not normally induced in pristane-inoculated BALB/cJ mice (26) are detected in CD1d<sup>+</sup> mice. This exacerbation of disease activity is associated with: 1) reduced TNF-α and IL-4 production by T cells, especially during the disease induction phase; and 2) expansion of marginal zone B cells. Strikingly, pristane inoculation by itself results in reduced NKT cell numbers and functions and decreased numbers of CD1d-expressing DCs and B cells.

Our observations suggest a regulatory role of CD1d-restricted events and that depletion of NKT cells or reduction in their functions may participate in the development of lupus. Indeed, patients with lupus and other systemic autoimmune diseases have reduced numbers of NKT cells (9–11). The CD1d1, a marker of NK/NKT cells, is the most significantly decreased lineage marker in the

![FIGURE 9](http://www.jimmunol.org/)

**FIGURE 9.** Effect of pristane inoculation and CD1d deficiency on marginal zone B cells. CD1d<sup>+</sup> or CD1d<sup>o</sup> mice were injected with PBS or pristane and sacrificed on day 11 or 30. Their spleen cells were stained with CD21, CD23, and B220 and analyzed by flow cytometry. Marginal zone B cells (CD21<sup>high</sup>CD23<sup>low</sup>) are shown as the mean ± SE (percent) of B220<sup>+</sup> cells on day 30 (a) or on days 11 and 30 (b) after injection with PBS or pristane. Note 1.5- to 2-fold expansion of marginal zone B cells on day 30, but not on day 11, in pristane-injected mice. Results represent three independent experiments (n = 2–4 mice/group). c, Serum total IgG3 levels (mean ± SE, μg/ml) in CD1d<sup>+</sup> and CD1d<sup>o</sup> BALB/c mice 9–12 mo after pristane injection (n = 13–16 mice/group, p < 0.02).

![FIGURE 10](http://www.jimmunol.org/)

**FIGURE 10.** α-GalCer-stimulated T cells can decrease autoantibody production by LPS-activated B cells from pristane-inoculated mice in vitro. Splenic B cells from BALB/c mice 6 mo after pristane inoculation were cocultured with splenic T cells from PBS-injected control animals, with or without α-GalCer. Supernatants collected on day 6 were tested for rheumatoid factor, which are expressed as the mean ± SD triplicate OD.
Peripheral blood cells of patients with SLE, as revealed in a recent gene expression study (31). Importantly, lupus disease activity appears to inversely correlate with numbers of circulating NKT cells in patients with SLE (10). Lupus-prone NZB/NZW F1 mice, when rendered deficient in CD1d, also experience an exacerbation of lupus nephritis (J.-Q. Yang, L. V. Kaer, and R. R. Singh, manuscript in preparation), albeit less profound than in the pristane model. Old (>1.5 years) CD1d0 BALB/c mice also have increased serum anti-DNA Ab levels as compared with age-matched controls (S. Porcelli, personal communication). A more direct evidence of NKT cell involvement in regulation of lupus-like autoimmunity comes from aging B6 Jx18 knockout mice which have elevated anti-DNA and anti-cardiolipin Abs and renal IgG and complement deposition as compared with age-matched B6 controls (S. Porcelli, F. Dieli, and G. Sireci, personal communication). In MRL-lpr/lpr mice, however, CD1d deficiency does not worsen kidney disease or anti-DNA Ab production (32). The regulatory effect of CD1d-restricted events on nephritis may require intact Fas signaling that is absent in MRL-lpr/lpr mice or the antiapoptotic effects of mutant Fas ligand are able to bypass the role of CD1d-reactive T cells. Furthermore, mechanisms of tissue damage appear to differ between different manifestations of lupus in the same or in different animal models of lupus (22, 32), which probably represent different subsets of this heterogeneous disease in humans. For example, mouse strains that develop anti-DNA Abs and kidney disease represent ~50% patients with SLE who develop these manifestations (reviewed in Ref. 33). Pristane-injected BALB/c mice, which develop mesangial and focal kidney lesions (Ref. 24 and Fig. 1), may represent ~50% of patients with lupus nephritis, whereas NZB/NZW F1 and MRL-lpr/lpr mice, which develop diffuse proliferative nephritis (7, 22), may represent ~30% patients with lupus nephritis (reviewed in Ref. 33). It is, therefore, not surprising that different mechanisms may operate in the development of lupus in various animal models. It is also possible that many functionally distinct subsets of CD1d-reactive T cells may exist; while some may promote autoimmune responses (34), others inhibit autoimmune disease (34, 35). For example, implantation of transgenic T cells that express the TCR-α and -β chain genes from a T cell clone, which is CD1d specific but does not express the invariant Vα14 NKT TCR, induces a lupus-like disease in irradiated BALB/c nude recipients, whereas another subset of CD1d-reactive T cells prevents the development of lupus in the same model (34).

There are multiple mechanisms that may explain why impairment or absence of CD1d-regulated events in pristane-injected wild-type and CD1d0 mice, respectively, would render them more susceptible to lupus (Fig. 11). First, abnormalities in cytokine production may contribute to the induction of autoimmunity in pristane-inoculated mice and its exacerbation in CD1d0 animals. We found that invariant NKT cells in pristane-inoculated mice express lesser amounts of IL-4 and higher amounts of IFN-γ (Fig. 5f). In patients with another autoimmune disease, multiple sclerosis, remission from disease is associated with a Th2 bias of CD4+ NKT cells (35), supporting our interpretation that lack of IL-4-secreting NKT cells may contribute to the exacerbation of autoimmune disease. Since activation of NKT cells by CD1d and α-GalCer may direct conventional T cells to the acquisition of a Th2 phenotype (27), decrease or absence of NKT cells may result in a Th1 bias of conventional T cells. Indeed, anti-CD3 or Con A-stimulated T cells from pristane-injected CD1d-deficient mice exhibit decreased IL-4 production along with stable IFN-γ production (Fig. 3). Such a cytokine milieu may be detrimental in pristane-inoculated mice, since IL-4 deficiency is known to accelerate autoantibody production in pristane-induced lupus (24). Furthermore, T cells from pristane-inoculated wild-type and CD1d0 mice produce smaller amounts of TNF-α during the early phase of disease development (Fig. 4, middle panel). This finding is important since low levels of TNF-α are believed to trigger an initial step toward the development of renal disease in lupus-prone mice (36, 42).
When rendered deficient in TNF-α, NZB mice, which generally develop only a very mild autoimmune disease, exhibit a more severe form of nephritis (38). In our experiments, TNF-α levels increase at 6 mo after pristane injection, i.e., the time when these animals begin to develop kidney disease (Fig. 4, right panel). These findings are consistent with previous reports showing that treatment with TNF-α initiated at a young age improves lupus nephritis (36), whereas administration of TNF-α at a later age accelerates nephritis (39). Thus, reduced TNF-α and IL-4 production by T cells during the early phase of disease development may contribute to the induction of lupus in wild-type mice and to exacerbation of disease in CD1d− mice.

Second, NKT cells appear to play a critical role in the development of immune tolerance (40), which is promoted by the expression of CD1d on APC (41). Thus, a decrease in CD1d-expressing DCs in pristane-injected wild-type mice (Fig. 8) and a lack of these cells in CD1d− mice might make these mice more susceptible to the loss of immune tolerance and induction of pathologic autoimmunity. In fact, our preliminary results suggest that CD8α−CD11b−CD11c− cells that correspond to CD1d−CD11c− cells (42) are reduced in the bone marrow of pristane-injected CD1d− mice (data not shown).

Finally, CD1dhigh B cells that correspond to marginal zone (CD21−CD23low) B cells are increased in pristane-injected mice, and IgG3 isotype, which is generally produced by marginal zone B cells (29), is significantly increased in CD1d− mice compared with wild-type littermates (Fig. 9). These observations lead us to speculate that NKT cells may regulate the expansion and activation of marginal zone B cells in CD1d− mice, which is highly expressed on T cells during the early phase of disease development may contribute to the induction of lupus in wild-type mice and to exacerbation of disease in CD1d− mice.

Fifth, decreased NKT cell numbers in pristane-induced lupus. These observations lead us to speculate that NKT cells may regulate the expansion and activation of marginal zone B cells in CD1d− mice, which is highly expressed on T cells during the early phase of disease development may contribute to the induction of lupus in wild-type mice and to exacerbation of disease in CD1d− mice.

In summary, pristane inoculation that causes lupus-like disease itself induces a state of invariant NKT cell deficiency in BALB/c mice (Fig. 11). Some invariant NKT cell functions begin to decline within hours of pristane injection. We then begin to detect a decrease in numbers of invariant NKT cells in the thymus and of functional (cytokine-secreting) NKT cells in the spleen along with a bias in the remaining NKT cells toward a Th1 phenotype.

Finally, CD1d expression on DCS (Fig. 8) may also contribute to the decreased NKT cell functions in pristane-inoculated mice, since CD1d-expressing cells are known to play a role in the activation and maintenance of NKT cells (49). Finally, it is also possible that the effects of CD1d deficiency on the lupus disease process are unrelated to any direct effects of pristane on the responses of CD1d-restricted T cells.

Acknowledgments

We thank M. Hirakata for help with anti-OJ Ab confirmation; K. Belney, V. Saxena, and H. Liu for technical help; D. Adams for advice; M. Shlomчик for reagents for rheumatoid factor assay; and Kirin Brewery Co. Ltd. for providing synthetic α-GalCer.

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