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Stimulation of Host NKT Cells by Synthetic Glycolipid Regulates Acute Graft-versus-Host Disease by Inducing Th2 Polarization of Donor T Cells

Daigo Hashimoto, Shoji Asakura, Sachiko Miyake, Takashi Yamamura, Luc Van Kaer, Chen Liu, Mitsune Tanimoto, and Takanori Teshima

NKT cells are a unique immunoregulatory T cell population that produces large amounts of cytokines. We have investigated whether stimulation of host NKT cells could modulate acute graft-vs-host disease (GVHD) in mice. Injection of the synthetic NKT cell ligand α-galactosylceramide (α-GalCer) to recipient mice on day 0 following allogeneic bone marrow transplantation promoted Th2 polarization of donor T cells and a dramatic reduction of serum TNF-α, a critical mediator of GVHD. A single injection of α-GalCer to recipient mice significantly reduced morbidity and mortality of GVHD. However, the same treatment was unable to confer protection against GVHD in NKT cell-deficient CD1d knockout (CD1d−/−) or IL-4−/− recipient mice or when STAT6−/− mice were used as donors, indicating the critical role of host NKT cells, host production of IL-4, and Th2 cytokine responses mediated by donor T cells on the protective effects of α-GalCer against GVHD. Thus, stimulation of host NKT cells through administration of NKT ligand can regulate acute GVHD by inducing Th2 polarization of donor T cells via STAT6-dependent mechanisms and might represent a novel strategy for prevention of acute GVHD. The Journal of Immunology, 2005, 174: 551–556.

1 This work was supported by research funds from the Ministry of Education, Culture, Sports, Science and Technology Grant 15591007 (to T.T.), by the Health and Labor Science Research Grants for Clinical Research for Evidence Based Medicine (to T.T.), by grants from the Ministry of Health, Labour, and Welfare of Japan (to T.T.), by the Organization for Pharmaceutical Safety and Research (to T.Y.), and by a grant-in-aid for cancer research from the Fukuoka Cancer Society. 2 Address correspondence and reprint requests to Dr. Takanori Teshima, Center for Cellular and Molecular Medicine, Kyushu University Hospital, 3-1-1 Maidashi, Higashi-ku, Fukuoka 812-8582, Japan. E-mail address: teshima@cancer.med.kyushu-u.ac.jp 3 Abbreviations used in this paper: HSCT, hematopoietic stem cell transplantation; BM, bone marrow; GVHD, graft-vs-host disease; DC, dendritic cell; α-GalCer, α-galactosylceramide; BMT, bone marrow transplantation; TBI, total body irradiation; TCD, T cell depletion; LN, lymph node; WT, wild type.
α-galactosylceramide (α-GalCer) (26), a glycolipid originally purified from a marine sponge, and its analog, OCH (27). Our findings indicate that stimulation of host NKT cells with NKT ligands can modulate acute GVHD.

Materials and Methods

Mice

Female C57BL/6 (B6, H-2b) and BALB/c (H-2d) mice were purchased from Charles River Japan. IL-4−/− B6 and STAT6−/− BALB/c mice were purchased from The Jackson Laboratory. CD1d−/− B6 mice were established by specific deletion of the CD1d1 gene segment (22). Mice, between 8 and 16 wk of age, were maintained in a specific pathogen-free environment and received chow and hyperchlorinated drinking water for the first 3 wk post-bone marrow transplantation (BMT). All experiments involving animals were performed under the auspices of the Institutional Animal Care and Research Advisory Committee at the Department of Animal Resources, Okayama University Advanced Science Research Center.

Bone marrow transplantation

Mice were transplanted according to a standard protocol described previously (28). Briefly, B6 mice received lethal total body irradiation (TBI; x-ray), split into two doses separated by 6.5 h to minimize gastrointestinal toxicity. Recipient mice were injected with 5 × 106 BM cells plus 5 × 106 spleen cells from either syngeneic (B6) or allogeneic (BALB/c) donors. T cell depletion (TCD) of donor BM cells was performed using anti-CD90 MicroBeads and the AutoMACS system (Miltenyi Biotec) according to the manufacturer’s instructions. Donor cells were resuspended in 0.25 ml of HBSS (Invitrogen Life Technologies) and injected i.v. into recipients on day 0. Survival was monitored daily. The degree of systemic acute GVHD was assessed weekly by a scoring system incorporating five clinical parameters: weight loss, posture (hunching), activity, fur texture, and skin integrity, as described (29).

Glycolipids

α-GalCer, (25,35,4R)-1-O-(α-D-galactopyranosyl)-2-(3-O-hexacosanoylamino)-1,3,4-octadecanetriol (KRN7000), was synthesized and provided by Kırı̇n Brewery Company (30). A homologue of α-GalCer, OCH, was selected from a panel of synthesized α-GalCer analogues by replacing the sugar moiety and/or truncating the aliphatic chains, because of its ability to stimulate enhanced IL-4 and reduced IFN-γ production by NKT cells, as previously described (27, 31). BMT recipient mice were injected i.p. with α-GalCer or OCH (100 μg/kg) immediately after BMT on day 0. Mice from the control groups received the diluent only.

Flow cytometric analysis

mAbs used were FITC- or PE-conjugated anti-mouse CD4, H-2Kd, and H-2Kk (BD Pharmingen). Cells were preincubated with 2.4G2 mAb (rat anti-mouse FcγR) for 10 min at 4°C to block nonspecific binding of labeled Abs, and then were incubated with the relevant mAbs for 15 min on ice. Finally, cells were washed twice with 0.2% BSA in PBS and fixed. After lysis of RBCs with FACS lysing solution (BD Pharmingen), cells were analyzed using a FACS caliber flow cytometer (BD Biosciences). 7-Amino-actinomycin D (BD Pharmingen)-positive cells (i.e., dead cells) were excluded from the analysis. Fluorochrome-conjugated irrelevant IgG were used as negative controls. At least 5000 live events were acquired for analysis.

Cell cultures

Mesenteric lymph nodes (LN) and spleens were removed from animals 6 days after BMT and four to six mesenteric LN or spleens from each experimental group were combined. Numbers of cells were normalized for T cells and were cultured in complete DMEM (Invitrogen Life Technologies) supplemented with 10% FCS, 50 U/ml penicillin, 50 μg/ml streptomycin, 2 mM l-glutamine, 1 mM sodium pyruvate, 0.1 mM nonessential amino acids, 0.02 mM 2-ME, and 10 mM HEPES in wells of a 96-well flat-bottom plate, at a concentration of 5 × 104 T cells/well with 1 × 105 irradiated (20 Gy) peritoneal cells harvested from naïve B6 (allogeneic) animals, or with 5 μg/ml plate-bound anti-CD3e mAbs (BD Pharmingen) and 2 μg/ml anti-CD28 mAbs (BD Pharmingen). Forty-eight hours after the initiation of culture, supernatants were collected for the measurement of cytokine levels.

ELISA

ELISA was performed according to the manufacturer’s protocols (R&D Systems) for measurement of IFN-γ, IL-4, and TNF-α levels, as described previously (32). Samples were obtained from culture supernatant and blood from retro-orbital plexus, diluted appropriately, and run in duplicate. Plates were read at 450 nm using a microplate reader (Bio-Rad). The sensitivity of the assays was 31.25 pg/ml for IFN-γ, 7.6 pg/ml for IL-4, and 23.4 pg/ml for TNF-α.

Histology

Formalin-preserved livers and small and large bowels were embedded in paraffin, cut into 5-μm-thick sections, and stained with H&E for histological examination. Slides were coded without reference to prior treatment group or examined in a blinded fashion by a pathologist (C. Liu). A semiquantitative scoring system was used to assess the following abnormalities known to be associated with GVHD, as previously described (33): 0, normal; 0.5, focal and rare; 1.0, focal and mild; 2.0, diffuse and mild; 3.0, diffuse and moderate; and 4.0, diffuse and severe. Scores were added to provide a total score for each specimen. After scoring, the codes were broken and data were compiled. Pathological GVHD scores of intestine are the sum of scores for small bowel and colon.

Statistical analysis

Mann-Whitney U test was applied for the analysis of cytokine data and clinical scores. We used the Kaplan-Meier product limit method to obtain survival probability, and the log-rank test was applied for comparing survival curves. Differences in pathological scores between the α-GalCer-treated group and the diluent-treated group were examined by two-way ANOVA. We defined p < 0.05 as statistically significant.

Results

Administration of α-GalCer stimulates lethally irradiated mice to produce IFN-γ and IL-4

We first determined whether administration of synthetic NKT ligands such as α-GalCer and OCH can stimulate heavily irradiated mice to produce cytokines. B6 mice were given 13 Gy TBI and were injected i.p. with α-GalCer, OCH, or diluent 2 h after TBI. Six hours later, blood samples were obtained, and serum samples were prepared for measurement of IFN-γ and IL-4. TBI alone or BMT itself did not stimulate diluent-treated mice to produce IFN-γ or IL-4 (Fig. 1). Administration of α-GalCer increased serum levels of IFN-γ and IL-4, even in mice receiving TBI. However, serum levels of IFN-γ were much less in irradiated mice than in unirradiated mice. By contrast, the ability of irradiated mice to produce IL-4 to α-GalCer was maintained for 48 h after irradiation. Serum levels of IFN-γ and IL-4 in response to α-GalCer were not altered when irradiated wild-type (WT) mice were injected with 5 × 106 BM cells and 5 × 106 spleen cells isolated from allogeneic (BALB/c) donors. Furthermore, these cytokine responses were not observed when α-GalCer was injected into irradiated NKT cell-deficient CD1d−/− mice with or without BMT. These results suggest that host NKT cells that survive for at least 48 h after irradiation, rather than from infused donor cells, are critically involved in the production of these cytokines in response to glycolipids. Irradiation appears to impair the ability of mice to produce IFN-γ while preserving IL-4 production in response to α-GalCer. Similar cytokine profiles were observed when OCH was administered (data not shown).

Administration of α-GalCer to recipients polarizes donor T cells toward Th2 cytokine production after allogeneic BMT

Induction of GVHD fundamentally depends upon donor T cell responses to host alloantigens. We next evaluated the effect of glycolipid administration on donor T cell responses after allogeneic BMT in a well-characterized murine model of acute GVHD (BALB/c→B6) directed against both MHC and multiple minor histocompatibility Ags. Lethally irradiated B6 mice were transplanted with 5 × 106 BM cells and 5 × 106 spleen cells from...
either syngeneic (B6) or allogeneic (BALB/c) donors. Immediately after BMT, B6 recipients were injected i.p. with either α-GaLCer or diluent. Six days after BMT, T cells isolated from mesenteric LN of recipient mice were cultured with irradiated B6 peritoneal cells or with anti-CD3ε mAbs and anti-CD28 mAbs for 48 h, and cytokine levels in the supernatant were determined. Flow cytometric analysis showed that >97% of LN T cells from both control recipients and α-GaLCer-treated recipients were donor derived, as assessed by H-2b vs H-2b expression. T cells from α-GaLCer-treated mice secreted significantly less IFN-γ, but more IL-4, in response to host alloantigens (Fig. 2, A and B) or to CD3 stimulation (Fig. 2, C and D) compared with those from controls. Similar results were obtained when T cells isolated from spleens were stimulated by anti-CD3ε and anti-CD28 mAbs. T cells from α-GaLCer-treated mice secreted significantly less IFN-γ (18 ± 2 vs 164 ± 6 ng/ml), but more IL-4 (1022 ± 114 vs 356 ± 243 pg/ml), compared with controls. These results demonstrate that a single injection of α-GaLCer to BMT recipients polarizes donor T cells toward Th2 responses after allogeneic BMT.

In α-GaLCer-treated mice, serum levels of IFN-γ were dramatically reduced on day 6 compared with controls (Fig. 3A), and IL-4, which is usually hardly detectable in serum in this model, failed to be detected in the serum of mice of either group (data not shown). This impaired Th1 response of donor T cells was associated with a marked reduction of TNF-α levels in α-GaLCer-treated mice (Fig. 3B).

Administration of α-GaLCer or OCH to BMT recipients modulates acute GVHD

We next examined whether immune deviation mediated by administration of glycolipids can modulate acute GVHD. BMT was performed as above and α-GaLCer was injected immediately after BMT on day 0. GVHD was severe in allogeneic controls, with 27% survival at day 50. A single injection of α-GaLCer significantly improved survival to 86% (p < 0.05) (Fig. 4A). Allogeneic control mice developed significantly more severe clinical GVHD compared with syngeneic controls, as assessed by clinical GVHD scores (Fig. 4B). Clinical GVHD scores were significantly reduced in α-GaLCer-treated recipients compared with allogeneic controls, but were greater than in syngeneic controls. Histological analysis showed that administration of α-GaLCer significantly suppressed GVHD pathological scores in the intestine (p < 0.05). Analysis of donor cell engraftment at day 60 after BMT in spleens showed complete donor engraftment in α-GaLCer-treated recipients (>99% H-2Kd+/H-2Kb− donor chimerism), ruling out rejection or mixed chimerism as a potential cause of GVHD suppression.

Similar protective effects against GVHD were observed in mice treated with OCH, further confirming the protective effects of NKT ligands (Fig. 4C). We performed BMT from B6 donors to BALB/c recipients to rule out strain artifacts. Again, a single injection of α-GaLCer to BALB/c recipients reduced GVHD and significantly improved survival of animals (Fig. 4D).

Host NKT cells and host production of IL-4 are required for suppression of GVHD by α-GaLCer

We examined the requirement of host NKT cells in this protective effect of α-GaLCer, using NKT cell-deficient CD1d−/− mice as
BMT recipients. Lethally irradiated CD1d−/− mice were transplanted with BM cells and spleen cells from WT BALB/c donors, followed by administration of α-GalCer immediately after BMT on day 0. Protective effects of α-GalCer administration were not observed when CD1d−/− B6 mice were used as recipients, confirming the requirement for host NKT cells (Fig. 5A). We next examined the requirement of IL-4 production by host cells in this protective effect. Lethally irradiated IL-4−/− B6 mice were transplanted from WT BALB/c donors and administered α-GalCer as above. α-GalCer did not confer protection against GVHD in IL-4−/− recipients (Fig. 5B). Taken together, these results indicate that protective effects of α-GalCer are dependent upon host NKT cells and host production of IL-4.

**STAT6 signaling in donor T cells is required for modulation of GVHD by α-GalCer**

To determine whether IL-4-induced signaling in donor T cells is critical for the protective effect of glycolipids on GVHD, we used donor spleen cells that lack STAT6 and have impaired IL-4 responses (34, 35). Spleen cells from STAT6−/− BALB/c mice and TCD BM cells from WT BALB/c mice were transplanted after lethal TBI, followed by a single injection of α-GalCer. α-GalCer treatment failed to reduce morbidity and mortality of acute GVHD when STAT6−/− BALB/c donors were used (Fig. 6), demonstrating that STAT6 signaling in donor cells is critical for the protective effect of α-GalCer against GVHD.

**FIGURE 3.** A single injection of α-GalCer to recipients of allogeneic BMT markedly reduces serum levels of IFN-γ and TNF-α. WT B6 mice were transplanted as in Fig. 2. Sera (n = 3–10/group) were obtained from diluent-treated (□) and α-GalCer-treated (■) recipients on day 6 after BMT, and serum levels of IFN-γ (A) and TNF-α (B) were determined. Results from three similar experiments are combined and shown as the mean ± SD. *p < 0.05 vs allogeneic, diluent-treated group. ND, Not detected; Syn, syngeneic; Allo, allogeneic.

**FIGURE 4.** A single injection of NKT ligands to BMT recipients modulates acute GVHD. BMT was performed as in Fig. 2. A, Survival curves of syngeneic control group (C, solid line; n = 9); allogeneic, diluent-treated recipients (∆, dotted line; n = 15); and allogeneic, α-GalCer-treated recipients (●, solid line; n = 14) are shown. Data from three similar experiments were combined. B, Clinical scores of syngeneic control group (C, solid line; n = 6); allogeneic, diluent-treated recipients (∆, dotted line; n = 10); and allogeneic, α-GalCer-treated recipients (●, solid line; n = 10) are shown. Data from two similar experiments were combined. C, Survival curves of syngeneic control group (C, solid line; n = 6); allogeneic, diluent-treated recipients (∆, dotted line; n = 10); and allogeneic, α-GalCer-treated recipients (●, solid line; n = 10) are shown. Data from two similar experiments were combined. *p < 0.05 vs diluent-treated group.

**FIGURE 5.** Host NKT cells and host IL-4 production are required for suppression of GVHD by α-GalCer. A, Lethally irradiated CD1d−/− B6 mice were transplanted as in Fig. 2. Survival curves of syngeneic control group (C, solid line; n = 6); allogeneic, diluent-treated recipients (∆, dotted line; n = 10); and allogeneic, α-GalCer-treated recipients (●, solid line; n = 10) are shown. Data from two similar experiments were combined. B, Lethally irradiated IL-4−/− B6 mice were transplanted as in Fig. 2. Survival curves of syngeneic control group (C, solid line; n = 11); allogeneic, diluent-treated recipients (∆, dotted line; n = 14); and allogeneic, α-GalCer-treated recipients (●, solid line; n = 14) are shown. Data from three similar experiments were combined.

**FIGURE 6.** The protective effects of α-GalCer against GVHD are dependent upon the STAT6 pathway of donor T cells. Lethally irradiated B6 mice were transplanted with TCD-BM cells (4 × 10⁵) from WT BALB/c mice and spleen cells (5 × 10⁶) from STAT6−/− BALB/c mice. A, Survival curves of the syngeneic control group (C, solid line; n = 15); allogeneic, diluent-treated recipients (∆, dotted line; n = 25); and allogeneic, α-GalCer-treated recipients (●, solid line; n = 25) are shown. Data from five similar experiments were combined. B, Clinical GVHD scores of syngeneic control group (C, solid line); allogeneic, diluent-treated recipients (∆, dotted line); and allogeneic, α-GalCer-treated recipients (●, solid line) are shown as the mean ± SE.
Discussion

NKT cells are critically involved in the development and suppression of various autoimmune diseases. In experimental models, their regulatory mechanisms mostly depend on IL-4 production and subsequent inhibition of Th1 differentiation of autoreactive CD4\(^+\) T cells (18). Previous studies have demonstrated that donor NKT cells regulate acute GVHD in an IL-4-dependent manner when administered together with donor inoculum (36). Considering these immunomodulating functions of NKT cells, we evaluated whether stimulation of host NKT cells could modulate GVHD in a mouse model of this disease.

Administration of \(\alpha\)-GalCer stimulates NKT cells to produce both IFN-\(\gamma\) and IL-4 in naive mice, which can promote Th1 and Th2 immunity, respectively (18). We first determined whether administration of synthetic NKT ligands such as \(\alpha\)-GalCer and OCH can stimulate heavily irradiated mice to produce cytokines. Surprisingly, irradiation of mice dramatically reduced IFN-\(\gamma\) production in response to \(\alpha\)-GalCer, while preserving IL-4 production. This result may account for Th2, but not Th1, polarization of donor T cells by \(\alpha\)-GalCer, even in conditions such as allogeneic BMT, which preferentially promotes Th1 polarization. Although mechanisms of selective suppression of IFN-\(\gamma\) production induced by irradiation need to be elucidated, irradiation may modulate the cytokine production profile of NKT cells or neighboring NK cells. Although OCH stimulates NKT cells to predominantly produce IL-4 compared with \(\alpha\)-GalCer, resulting in potent Th2 responses (27, 31), both OCH and \(\alpha\)-GalCer equally stimulate IL-4 production in irradiated mice and exert equivalent protection against acute GVHD.

Stimulation of host NKT cells by injecting \(\alpha\)-GalCer or OCH polarized donor T cells toward Th2 cytokine secretion, resulting in marked reduction of serum IFN-\(\gamma\) levels after BMT. Th2 cytokine responses subsequently inhibited inflammatory cytokine cascades and reduced morbidity and mortality of acute GVHD, as previously described (10–12). Inflammatory cytokines have been shown to be important effector molecules of acute GVHD (37). \(\alpha\)-GalCer treatment failed to confer protection against acute GVHD when STAT6\(^{-/-}\) BALB/c donors were used, demonstrating that Th2 polarization via STAT6 signaling is critical for this protective effect of \(\alpha\)-GalCer, although STAT6-independent Th2 induction has been reported (38, 39).

\(\alpha\)-GalCer did not confer protection against GVHD in CD1d\(^{-/-}\) or IL-4\(^{-/-}\) recipients. Therefore, the protective effect of \(\alpha\)-GalCer against GVHD is dependent upon host NKT cells and host production of IL-4. Sublethal total lymphoid irradiation enriches NKT cells in host lymphoid tissues, and these NKT cells induce Th2 polarization of conventional T cells by IL-4 production, resulting in reduced GVHD (40–42). These findings are consistent with our observation that IL-4 production is critical for the protective effects of NKT cells against acute GVHD. It should be noted, however, that systemic administration of IL-4 is either ineffective or toxic (6). Because the cytokine environment during the initial interaction between naive T cells and APCs is critically important for induction of Th1 or Th2 differentiation (14), local IL-4 production in the secondary lymphoid organs where donor T cells encounter host APCs might be necessary to cause effective Th1\(\rightarrow\)Th2 immune deviation after allogeneic HSCT (43).

Current strategies for prophylaxis and treatment of GVHD primarily target depletion or suppression of donor T cells. These interventions suppress donor T cell activation and are associated with increased risk of infection and relapses of malignant diseases. Th1\(\rightarrow\)Th2 deviation of donor T cells represents a promising strategy to reduce acute GVHD while preserving cytolytic cellular effector functions against tumors and infectious agents (33, 44–47). To achieve Th1\(\rightarrow\)Th2 immune deviation of donor T cells, cytokines have been administered to either donors or recipients in animal models of GVHD. Donor treatment with cytokines such as IL-18 and G-CSF, and recipient treatment with IL-11, induces Th2 polarization of donor T cells and reduces acute GVHD (33, 44, 48). The present study reveals an alternative strategy to induce Th2 polarization of donor T cells by injecting NKT ligands into recipients to activate recipient NKT cells.

Prior studies (36, 40–42, 49) and the current study suggest that both donor and host NKT cells can regulate acute GVHD through their unique properties to secrete large amounts of cytokines and subsequent modulation of adaptive immunity. These studies reveal that there are several ways by which the NKT cell system can be exploited to suppress GVHD. First, administration of donor NKT cells expanded in vitro by repeated stimulation with glycolipid (50) can suppress GVHD (36). Second, total lymphoid irradiation enriches host NKT cells in lymphoid organs and thereby skews donor T cells toward Th2 cytokine production (40–42). Third, as shown here, administration of glycolipid to recipients stimulates host NKT cells to suppress GVHD. A recent phase I trial for patients with various solid tumors demonstrated that administration of \(\alpha\)-GalCer was well tolerated with minimal side effects, which included temporal fever, headache, vomiting, chills, and malaise (51). Therefore, \(\alpha\)-GalCer treatment may provide an effective and relatively safe option for preventing GVHD.

Cells belonging to the innate arm of the immune system, such as monocytes/macrophages, NKT cells, and NK cells, can produce large amounts of cytokines quickly upon stimulation. Innate immunity can thereby augment donor T cell responses to alloantigens in allogeneic HSCT (3). Our findings reveal a novel role for host NKT cells in regulating GVHD and indicate that stimulation of host innate immunity may serve as an effective adjunct to clinical regimens of GVHD prophylaxis.

Acknowledgments

We thank Kirin Brewery Company for providing synthetic \(\alpha\)-GalCer and Keiatomic Matsuo for statistical analysis.

References


