

S-Adenosyl-L-homocysteine Hydrolase Inactivation Curtails Ovalbumin-Induced Immune Responses

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Received July 27, 2005; accepted November 30, 2005

ABSTRACT

The reversible S-adenosyl-L-homocysteine (AdoHcy) hydrolase inhibitor methyl 4-(adenin-9-yl)-2-hydroxybutanoate (DZ2002) suppresses macrophage activation and function. The effects of DZ2002 on T cell function, however, are still unclear. Here, we examined whether DZ2002 alters type 1 helper T cell (Th1) and/or type 2 helper T cell (Th2) immune responses, and whether these effects are associated with both the inhibition of AdoHcy hydrolase and intracellular elevation of endogenous AdoHcy. Male C57BL/6 mice immunized with ovalbumin (OVA) were treated with DZ2002 (1, 5, and 25 mg/kg/day) after which lymphocyte proliferation, cytokine production, and IgG responses to OVA were monitored. Administration of DZ2002 dose dependently suppressed OVA-specific lymphocyte proliferation and anti-OVA IgG production compared with controls.

Interleukin (IL)-2 and interferon (IFN)- γ as well as anti-OVA IgG2a and IgG3, indicators of Th1 immune responses, were markedly decreased in mice treated with DZ2002, whereas IL-4 and anti-OVA IgG1, indicators of Th2 immune responses, were only mildly suppressed. AdoHcy hydrolase activity in spleens of DZ2002-treated mice was substantially blocked, and not surprisingly, AdoHcy levels were significantly elevated compared with controls. Finally, similar immunosuppressive effects were also observed in mice treated with AdoHcy. These data strongly indicate that DZ2002 suppresses antigen-induced specific immune responses, particularly Th1 responses, through inhibition of AdoHcy hydrolase and elevation of endogenous AdoHcy.

S-Adenosyl-L-homocysteine (AdoHcy) hydrolase (EC 3.3.1.1) is a highly conserved ubiquitous enzyme of 432 amino acids that catalyzes the hydrolysis of AdoHcy to adenosine (Ado) and homocysteine (Hcy) in eukaryotic cells (Yuan et al., 1999). Conversely, inhibition of the AdoHcy hydrolase leads to the accumulation of intracellular levels of AdoHcy, a potent feedback inhibitor of all S-adenosyl-L-methionine-de-

pendent cellular transmethylation reactions, including methylations of proteins, lipids, and nucleic acids (Saso et al., 2001; Wu et al., 2005). Because lymphocytes seem more dependent upon transmethylation reactions than most other cell types for their activation/function (German et al., 1983), AdoHcy hydrolase is thought to be an attractive target for the design of immunosuppressive and anti-inflammatory agents.

In recent years, several AdoHcy hydrolase inhibitors have been characterized. These compounds block T cell proliferation and IL-2 production (Wolos et al., 1993b; Wu et al., 2005) and exhibit both prophylactic and therapeutic effects in T cell-mediated immune models, including 2,4-dinitrofluorobenzene (DNFB)-induced delayed-type hypersensitivity reac-

This research work was supported by Knowledge Innovation Program of Chinese Academy of Sciences Grant KSCX2-SW-202, Natural Science Research Foundation of China Grant 30572195, and Shanghai Science and Technology Committee Grant 03DZ19228.

Article, publication date, and citation information can be found at <http://jpet.aspetjournals.org>.
doi:10.1124/jpet.105.093369.

ABBREVIATIONS: AdoHcy, S-adenosyl-L-homocysteine; Ado, adenosine; Hcy, homocysteine; IL, interleukin; DNFB, 2,4-dinitrofluorobenzene; DZ2002, methyl 4-(adenin-9-yl)-2-hydroxybutanoate; MDL 28,842, (Z)-5'-fluoro-4',5'-didehydro-5'-deoxyadenosine; OVA, ovalbumin; Th1, type 1 helper T cell; Th2, type 2 helper T cell; DMSO, dimethyl sulfoxide; CFA, complete Freund's adjuvant; FCS, fetal calf serum; ELISA, enzyme-linked immunosorbent assay; IFN, interferon; PBS, phosphate-buffered saline; LN, lymph node; O.D., optical density; HPLC, high-performance liquid chromatography.

tions (Saso et al., 2001; Wu et al., 2005), allogeneic skin graft rejection, and collagen- (Wolos et al., 1993a,c) and peptidoglycan polysaccharide-induced arthritis (Saso et al., 2001). Although the precise mechanism(s) by which inhibition of AdoHcy hydrolase leads to the suppression of immune cell proliferation and activation is still unknown, three pathways have been proposed: 1) decrease in transmethylation reactions because of the accumulation of AdoHcy, 2) depletion of intracellular levels of homocysteine, and 3) blockade of necessary signaling molecules such as phosphatidyl inositol kinase (Wolos et al., 1993b; Saso et al., 2001; Wu et al., 2005). Thus far, the direct linkage between these pathways and immunosuppression has not been examined.

To date, three types of AdoHcy hydrolase inhibitors have been described: the irreversible type I and type II inhibitors and the reversible type III inhibitors (Yuan et al., 1999). These inhibitors either take advantage of the 3'-oxidative activity (type I) of AdoHcy hydrolase, thus becoming irreversibly trapped in the active site of the enzyme; and its 5'-hydrolytic activity, which permanently alters the active site (type II); or reversibly bind to the open form of the enzyme (type III). Because of the relatively long turnover rate of AdoHcy hydrolase ($t_{1/2}$ of ~24 h), the irreversible inhibitors manifest significant toxicity, whereas type III inhibitors show greatly reduced toxicity yet still retain a similar ability to block the enzyme's activity (Yuan et al., 1999).

Recently, we reported that a potent ($K_i = 17.9$ nM) type III inhibitor of AdoHcy hydrolase, DZ2002, obstructs both T cell and macrophage activation/function through down-regulation of cytokine production and costimulatory molecule expression (Wu et al., 2005). Moreover, DZ2002 treatment reduced DNFB-induced delayed-type hypersensitivity responses, indicating a direct inhibitory effect on T cells, in particular, CD4⁺ T cells (Wu et al., 2005).

In the present study, we used DZ2002 to test the hypothesis that blockade of AdoHcy hydrolase leads to thymus-dependent antigen-specific immunosuppression in ovalbumin (OVA)-immunized mice. We investigated the effects of DZ2002 on proliferative responses, cytokine levels, and antibody production after OVA immunization. In addition, we examined whether DZ2002 administration modulated Th1 versus Th2 type immune responses. Finally, to determine whether elevation of AdoHcy because of the inhibition of AdoHcy hydrolase by DZ2002 contributes to the immunosuppressive effects seen with DZ2002, we compared the effects of the methylation inhibitor AdoHcy (Boger et al., 2000a,b) with those of DZ2002 in OVA-immunized mice. We found that indeed, DZ2002 blocked OVA-specific T cell proliferation as well as anti-OVA IgG2a and IgG3 production. In addition, cytokine responses to OVA were decreased in DZ2002-treated mice and were associated with increased levels of intracellular AdoHcy.

Materials and Methods

Reagents. AdoHcy hydrolase inhibitor DZ2002 was synthesized at Diazyme Laboratories (San Diego, CA). OVA (grade V), dimethyl sulfoxide (DMSO), acetonitrile, AdoHcy, Ado, Hcy, Ado deaminase inhibitor erythro-9-(2-hydroxy-3-nonyl)-adenine hydrochloride, and 3,3',5,5'-tetramethylbenzidine were supplied by Sigma-Aldrich (St. Louis, MO). Complete Freund's adjuvant (CFA) was purchased from Difco (Detroit, MI). RPMI 1640 medium was purchased from Gibco BRL/Life Technologies Inc. (Gaithersburg, MD), and fetal calf serum

(FCS) was obtained from Hyclone Laboratories (Logan, UT). [³H]Thymidine was provided by The Shanghai Institute of Applied Physics, Chinese Academy of Sciences (Shanghai, People's Republic of China). ELISA kits for IL-2, IFN- γ , and IL-4 were purchased from BD PharMingen (San Diego, CA). Rabbit anti-mouse IgG, IgG1, IgG2a, or IgG3 antibodies labeled with horseradish peroxidase were purchased from Bio-Rad (Hercules, CA).

Animals. Male C57BL/6 mice, aged 6 to 8 weeks, were purchased from the Shanghai Experimental Animal Center, Chinese Academy of Sciences. All animals were housed in specific pathogen-free conditions. Experiments were carried out according to the National Institutes of Health Guide for Care and Use of Laboratory Animals and were approved by the Bioethics Committee of the Shanghai Institute of Materia Medica.

Experimental Protocol. OVA (2 mg/ml) was diluted in phosphate-buffered saline (PBS) and emulsified in an equal volume of CFA. Then, 100 μ g of OVA in the CFA emulsion was injected s.c. into two different sites on the backs of shaved mice ($n = 8$ mice/group). DZ2002 (1, 5, and 25 mg/kg/day) was dissolved in PBS containing 0.4% DMSO and administered i.p. after OVA immunization and continued throughout the study. Doses of DZ2002 were chosen on the basis of previous *in vivo* data (Wu et al., 2005) and our own preliminary experiments. As a control, an equal volume of PBS containing 0.4% DMSO was injected daily into control mice i.p. ($n = 8$ mice). As an additional control, the methylation inhibitor AdoHcy (0.2, 1, and 5 mg/kg/day) was dissolved in PBS containing 0.4% DMSO and also administered i.p. into mice ($n = 8$ mice) from days 0 to 21. Our own preliminary pharmacokinetic experiments determined that spleen levels of AdoHcy attained by direct injection (0.2~5 mg/kg AdoHcy) were 250~280 nmol/g spleen, corresponding to the concentrations that treatment with DZ2002 (1~25 mg/kg) achieved. The dosages of AdoHcy were selected based on previous reports that documented *in vivo* physiological effects (Fonlupt et al., 1979a,b; Gharib et al., 1985) and our own previously mentioned preliminary experiments.

Proliferation Assay. Spleens and draining lymph nodes (LNs) (axillary and inguinal) ($n = 8$ mice/group) were removed, and cell suspensions were prepared as described previously with minor modifications (Feng et al., 2002; Wu et al., 2005). In brief, erythrocytes were lysed with Tris-NH₄Cl. Remaining cells (5×10^5 cells/well) were then cultured in triplicate in 200 μ l of RPMI 1640 medium supplemented with 10% FCS, 1 mM glutamine, 100 U/ml penicillin, 100 μ g/ml streptomycin, and 2-mercaptoethanol in 96-well flat-bottomed plates (Corning Glassworks, Corning, NY) in the presence of 100 μ g/ml OVA. After 60 h, 0.5 μ Ci/well of [³H]thymidine was added to each well for 12 h, and cells were harvested onto glass fiber filters. [³H]Thymidine incorporation was measured by a MicroBeta TriLux liquid scintillation counter (PerkinElmer Life and Analytical Science, Boston, MA).

Cytokine Measurement. Splenocytes and draining LN cells ($n = 8$ mice/group) were prepared as described above. Cells (5×10^5 cells/well) were cultured in triplicate in 96-well flat-bottomed plates (Corning Glassworks) in the presence of 100 μ g/ml OVA. After 48 h, culture supernatants were harvested and stored at -20°C. Concentrations of IL-2, IL-4, and IFN- γ were determined by ELISA as described by the manufacturer.

Determination of OVA-Specific Antibody. Serum samples ($n = 6$ mice/group) were collected on day 21 after OVA immunization. Levels of OVA-specific total IgG, IgG1, IgG2a, and IgG3 antibodies were determined by ELISA as described previously (Yoshino et al., 2003, 2004). In brief, 96-well plates (Corning Glassworks) were coated with OVA (100 μ g/ml) overnight. Wells were washed with PBS containing 0.05% Tween 20 and then blocked with PBS containing 10% FCS. Next, serum samples were incubated for 30 min, plates were washed, and Ig subclasses were revealed using rabbit anti-mouse IgG, IgG1, IgG2a, or IgG3 conjugated to horseradish peroxidase and an appropriate substrate. Absorbance at 570 nm was read using a SpectraMax 190 microplate reader (Molecular Devices,

Sunnyvale, CA). Results are expressed as absorbance units at $O.D._{570} \pm S.E.M$ (Yoshino et al., 2003).

Determination of AdoHcy Hydrolase Activity. Spleens from mice ($n = 6$ mice/group) treated with increasing dosages of DZ2002 or vehicle were collected on day 21 after immunization with OVA. Tissue was homogenized in ice-cold saline, and after centrifugation at 3000g for 15 min at 4°C, the supernatant was collected and the protein concentration was determined by the Coomassie Brilliant Blue method (Fu et al., 2005). Supernatant was then used for the measurement of AdoHcy hydrolase activity.

Since AdoHcy hydrolase catalyzes the synthetic reaction from Ado and Hcy to AdoHcy as well as the hydrolytic reaction from AdoHcy to Ado and Hcy, AdoHcy hydrolase activity in spleens was determined in the synthetic direction by measuring the rate of AdoHcy formation from Ado and Hcy according to described previously methods (Yuan et al., 1994; Saso et al., 2001). In brief, 10 μ l of the supernatant obtained from splenocytes was added to 20 μ l of 10 mM Ado, 20 μ l of 1 mM Ado deaminase inhibitor erythro-9-(2-hydroxy-3-nonyl)-adenine hydrochloride, and 50 μ l of 62.5 mM Hcy. This solution was then added to 400 μ l of 50 mM potassium phosphate buffer, pH 7.2, containing 1 mM EDTA and incubated at 37°C for 10 min. The reaction was terminated by the addition of 20 μ l of 5 N HClO₄. After centrifugation, the supernatant was collected and analyzed for AdoHcy by HPLC (Agilent 1100; Agilent Technologies, Palo Alto, CA) using a C18 reversed phase column (Agilent Zorbax SB-C18; 5 μ m; 50 $\times$ 2.1 mm). The elution was carried out in two sequential linear gradients: 6 to 15% A over 0 to 9 min, 15 to 50% B over 9 to 15 min, where mobile phase A is acetonitrile and B is 50 mM sodium phosphate buffer, pH 3.2, containing 10 mM L-heptanesulfonic acid. The peak of AdoHcy was monitored at 258 nm, and the concentration of AdoHcy was determined by comparison of the area under the curve with that of a known quantity of AdoHcy using a standard curve. One unit of enzyme activity was defined as the amount of enzyme that can synthesize 1 μ mol of AdoHcy per minute per milligram of protein.

Measurement of AdoHcy in Spleen. Spleens were quickly excised from mice ($n = 6$ mice/group) that were treated with various dosages of DZ2002 or vehicle, snap frozen in liquid nitrogen, and stored at -80°C. Approximately 100 mg of spleen tissue was homogenized in four volumes of 0.4 M HClO₄. After centrifugation at 10,000g for 15 min at 4°C, the supernatant was filtered through a 0.2- μ m polypropylene syringe filter. A 5- μ l aliquot of the acid extract was applied directly onto the HPLC column as described previously (She et al., 1994; Wang et al., 2001). Results are expressed in nanomoles per gram of wet tissue.

Statistical Analysis. Results are expressed as mean $\pm$ S.E.M. One-way analysis of variance followed by Dunnett's post test was used to determine differences between groups where appropriate. $P < 0.05$ was considered significant.

Results

DZ2002 Reduces OVA-Induced Lymphocyte Proliferation and Cytokine Production. Recently, we reported that the reversible AdoHcy hydrolase inhibitor DZ2002 had little effect on concanavalin A-stimulated T cells with regard to either proliferation or IL-2 production (Wu et al., 2005). Here, we examined the effects of increasing concentrations of DZ2002 on OVA-induced lymphocyte proliferation at 1, 5, and 25 mg/kg/day. Seven, 14, and 21 days after OVA immunization ($n = 8$ mice/group), splenocytes and draining LN (axillary and inguinal) cells were assessed for their capacity to proliferate to OVA ex vivo. When splenocytes were stimulated with OVA at 100 μ g/ml, responses of DZ2002-treated mice were dose dependently decreased compared with splenocytes from vehicle-treated control mice. For example,

on day 21, proliferative responses to OVA were suppressed by 44, 55, and 70% at 1, 5, and 25 mg/kg DZ2002, respectively (1 mg/kg = $22,671 \pm 2126$, 5 mg/kg = $18,178 \pm 1783$, and 25 mg/kg = $12,171 \pm 1836$ cpm versus vehicle-treated = $40,388 \pm 1749$ cpm) (Fig. 1A). Likewise, when LN cells from DZ2002- and vehicle-treated mice were stimulated in vitro with OVA, proliferative responses were blocked in a dose-dependent manner in DZ2002-treated mice (Fig. 1B).

We then analyzed whether DZ2002 affected OVA-specific cytokine production from DZ2002- or vehicle-treated mice ($n = 8$ mice/group). We found that levels of IL-2, IL-4, and IFN- γ , produced by either splenocytes or LN cells, were decreased at all time points by prior treatment with DZ2002 (Fig. 2, A and B). Interestingly, DZ2002 administration seemed to reduce OVA-induced production of Th1-associated cytokines such as IL-2 and IFN- γ , more than the Th2-associated cytokine IL-4. As depicted in Fig. 2A, on day 21, the highest dosage (25 mg/kg/day) of DZ2002 showed ~83% inhibition of IL-2 (25 mg/kg = 20.9 ± 1.8 pg/ml versus vehicle-treated = 125.3 ± 4.7 pg/ml) and ~93% inhibition of IFN- γ production (25 mg/kg = 588.8 ± 34.3 pg/ml versus vehicle-treated = 8782.7 ± 37.4 pg/ml) from splenocytes, whereas

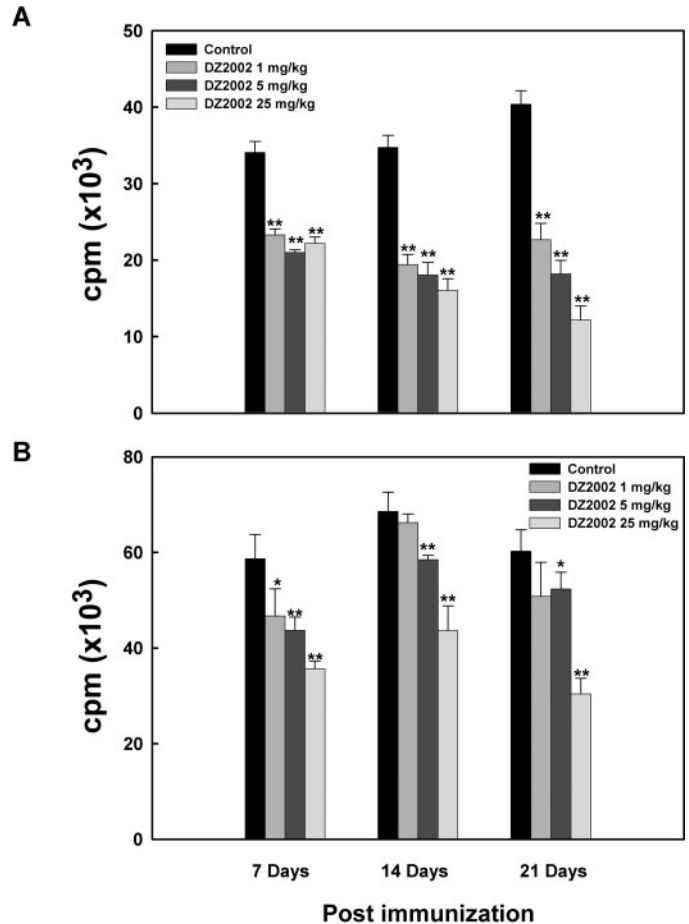
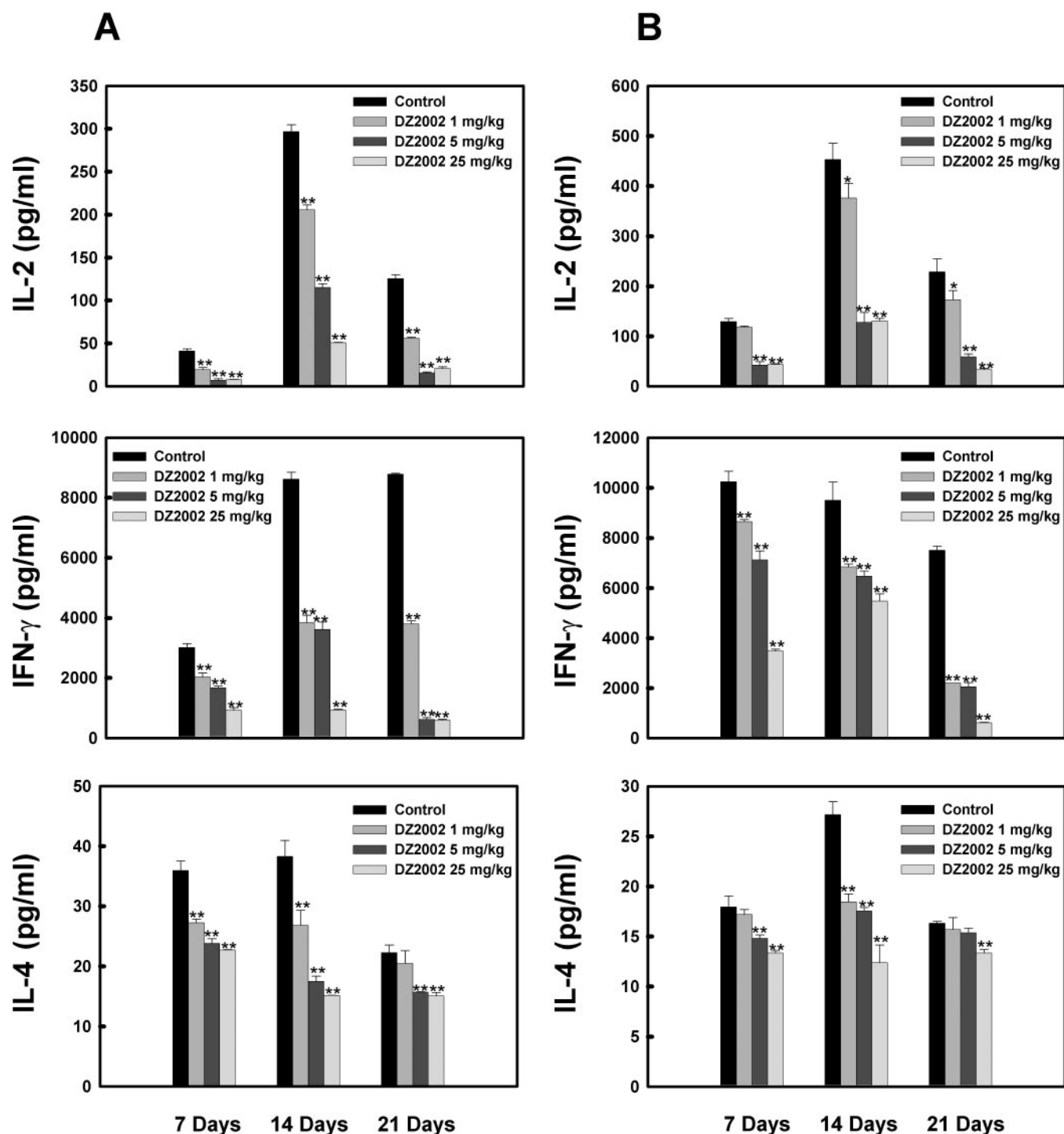


Fig. 1. Administration of DZ2002 inhibits OVA-induced splenocyte (A) and LN cell (B) proliferation. OVA-immunized mice were treated with DZ2002 at 1, 5, and 25 mg/kg/day by i.p. injection. On the indicated day, splenocytes and draining LN cells were recovered and 5×10^5 cells were incubated with 100 μ g/ml OVA for 72 h. Cultures were pulsed with 0.5 μ Ci/well [³H]thymidine for the final 12 h. Results are expressed as mean $\pm$ S.E.M. of eight mice. *, $P < 0.05$; **, $P < 0.01$ compared with vehicle control (Dunnett's test). Three independent experiments were performed with similar results.



Post immunization

Fig. 2. Administration of DZ2002 inhibits OVA-induced splenocyte (A) and LN cell (B) cytokine production. OVA-immunized mice were treated with DZ2002 at 1, 5, and 25 mg/kg/day by i.p. injection. On the indicated days, splenocytes and draining LN cells were recovered and 5×10^5 cells were incubated for 48 h with 100 μ g/ml OVA. Culture supernatants were collected and analyzed by ELISA for levels of IL-2, IL-4, and IFN- γ . Results are expressed as mean $\pm$ S.E.M. of eight mice. *, $P < 0.05$; **, $P < 0.01$ compared with vehicle control (Dunnett's test). Three independent experiments were performed with similar results.

only ~32% inhibition of IL-4 production was noted (25 mg/kg = 15.0 ± 0.6 pg/ml versus vehicle-treated = 22.2 ± 1.3 pg/ml). Likewise, the highest dosage (25 mg/kg/day) of DZ2002 showed ~86% inhibition of IL-2 (25 mg/kg = $33.2 \pm$

2.1 pg/ml versus vehicle-treated = 228.2 ± 26.1 pg/ml) and ~92% inhibition of IFN- γ production (25 mg/kg = 613.9 ± 22.7 pg/ml versus vehicle-treated = 7499.1 ± 147.7 pg/ml) by LN cells, whereas IL-4 was inhibited by only ~18% (25 mg/

kg = 13.3 ± 0.4 pg/ml versus vehicle-treated = 16.3 ± 0.2 pg/ml) (Fig. 2B). We tried to confirm that Th1-type cytokines were preferentially reduced compared with Th2 cytokines by quantitating a second Th2-associated cytokine, IL-5. Unfortunately, IL-5 levels were too low to detect in our assay (data not shown).

DZ2002 Blocks Anti-OVA IgG Antibody Production.

To examine the effects of DZ2002 on in vivo OVA-specific antibody production, serum levels of anti-OVA IgG, IgG1, IgG2a, and IgG3 antibodies were determined on day 21 ($n = 6$ mice/group). As depicted in Fig. 3, serum levels of total anti-OVA IgG in DZ2002-treated animals were significantly decreased compared with serum samples from vehicle-treated mice (Fig. 3). Treatment with 25 mg/kg/day DZ2002 showed 52% ($25 \text{ mg/kg} = 0.125 \pm 0.013$ versus vehicle-treated = 0.262 ± 0.035 O.D. units) and 67% ($25 \text{ mg/kg} = 0.172 \pm 0.040$ versus vehicle-treated = 0.523 ± 0.089 O.D. units) decreases in anti-OVA-IgG2a and IgG3 production, respectively, whereas a 44% ($25 \text{ mg/kg} = 0.333 \pm 0.082$ versus vehicle-treated = 0.594 ± 0.021 O.D. units) reduction in anti-OVA IgG1 levels was noted.

DZ2002 Inhibits AdoHcy Hydrolase Activity and Leads to the Accumulation of Intracellular AdoHcy. To examine whether inhibition of AdoHcy hydrolase is directly associated with immunosuppression in OVA-immunized mice, AdoHcy hydrolase activity was measured in spleens collected from DZ2002- and vehicle-treated mice ($n = 6$ mice/

group). We found that administration of DZ2002 reduced AdoHcy hydrolase activity (47.2, 48.6, and 51.5% at dosages of 1, 5, and 25 mg/kg/day, respectively; Fig. 4A) in treated mice ($1 \text{ mg/kg} = 18.9 \pm 1.1$, $5 \text{ mg/kg} = 18.5 \pm 0.6$, and $25 \text{ mg/kg} = 17.4 \pm 1.2$ nmol AdoHcy/min/mg protein versus vehicle-treated = 35.9 ± 1.8 nmol AdoHcy/min/mg protein). These data therefore suggested that, after DZ2002 treatment, AdoHcy is likely accumulating intracellularly in tissues and should be detected. Indeed, inhibition of AdoHcy hydrolase by DZ2002 resulted in the accumulation of intracellular AdoHcy (Fig. 4B). As predicted, AdoHcy levels in spleens of DZ2002-treated animals were modestly dose dependently elevated compared with spleen tissue from controls ($1 \text{ mg/kg} = 253.0 \pm 22.5$, $5 \text{ mg/kg} = 308.0 \pm 13.3$, and $25 \text{ mg/kg} = 381 \pm 19.6$ nmol/g spleen versus vehicle-treated = 233.0 ± 18.9 nmol/g spleen).

AdoHcy Also Suppresses OVA-Induced Immune Responses in Mice. Because DZ2002 potently blocks AdoHcy hydrolase activity and probably results in the accumulation of intracellular AdoHcy, the effects of increasing dosages of AdoHcy (0.2, 1, and 5 mg/kg) treatment in vivo on OVA-induced immune responses were investigated next. Administration of 1 and 5 but not 0.2 mg/kg/day AdoHcy resulted in significant decreases in proliferation of splenocytes (Fig. 5A) and LN cells (Fig. 5B) to OVA ($n = 8$ mice/group). Likewise, most Th1-associated responses to OVA, including IL-2 and IFN- γ secretion by both splenocytes (Fig. 6A) and LN cells

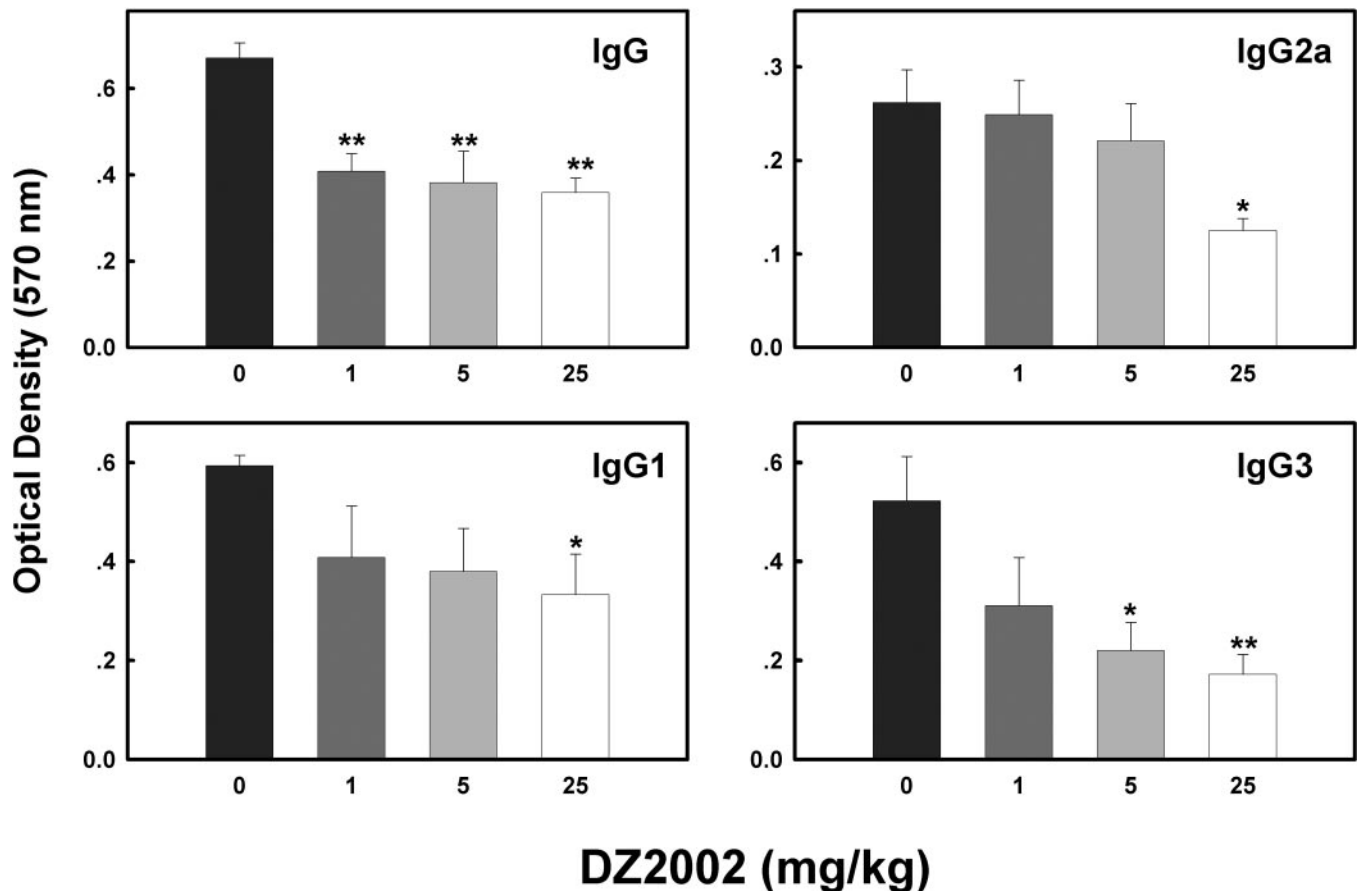


Fig. 3. Administration of DZ2002 reduces production of anti-OVA IgG antibody and its subclasses. OVA-immunized mice were treated with DZ2002 at 1, 5, and 25 mg/kg/day by i.p. injection. On day 21 postimmunization, anti-OVA IgG, IgG1, IgG2a, and IgG3 levels were determined by ELISA. Results are expressed as mean $\pm$ S.E.M. of six mice. *, $P < 0.05$; **, $P < 0.01$ compared with vehicle control (Dunnett's test). Three independent experiments were performed with similar results.

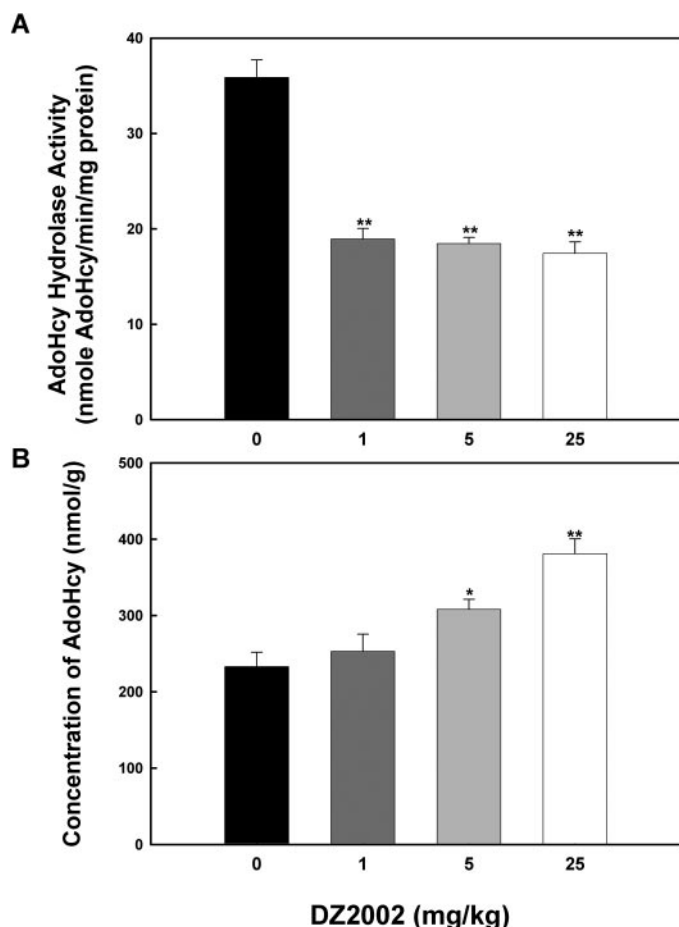


Fig. 4. In vivo administration of DZ2002 inactivates AdoHcy hydrolase (A) and leads to the intracellular accumulation of AdoHcy (B). OVA-immunized mice were treated with DZ2002 at 1, 5, and 25 mg/kg/day by i.p. injection. On day 21 postimmunization, spleens were harvested and the activity of AdoHcy hydrolase and levels of AdoHcy were determined by HPLC. One unit of enzyme activity was defined as the amount of enzyme that can synthesize 1 μ mol of AdoHcy/min/mg protein. AdoHcy levels are expressed in nanomoles per gram of wet tissue. Results are expressed as mean $\pm$ S.E.M. of six mice. *, $P < 0.05$; **, $P < 0.01$ compared with vehicle control (Dunnett's test). Three independent experiments were performed with similar results.

(Fig. 6B), and anti-OVA IgG2a and IgG3 production (Fig. 7), were decreased in mice given 0.2, 1, and 5 mg/kg/day AdoHcy, respectively ($n = 8$ or 6 mice/group). In contrast, Th2 responses to OVA, including IL-4 synthesis by lymphocytes (Fig. 6, A and B) and anti-OVA IgG1 production (Fig. 7), were only partially inhibited in mice given the same dosage of AdoHcy. These immunosuppressive effects of AdoHcy were similar to those of DZ2002.

Discussion

The present study demonstrated that treatment of mice with DZ2002 not only decreased OVA-induced lymphocyte proliferation and anti-OVA IgG antibody production but also suppressed Th1- and Th2-associated immune responses, in particular, Th1 responses. These effects were accompanied by inactivation of AdoHcy hydrolase activity, and by the accumulation of AdoHcy in the spleen. Moreover, similar to DZ2002 treatment of mice, treatment with AdoHcy also suppressed OVA-induced lymphocyte proliferation, anti-OVA IgG antibody production, and Th1- and Th2-type immune

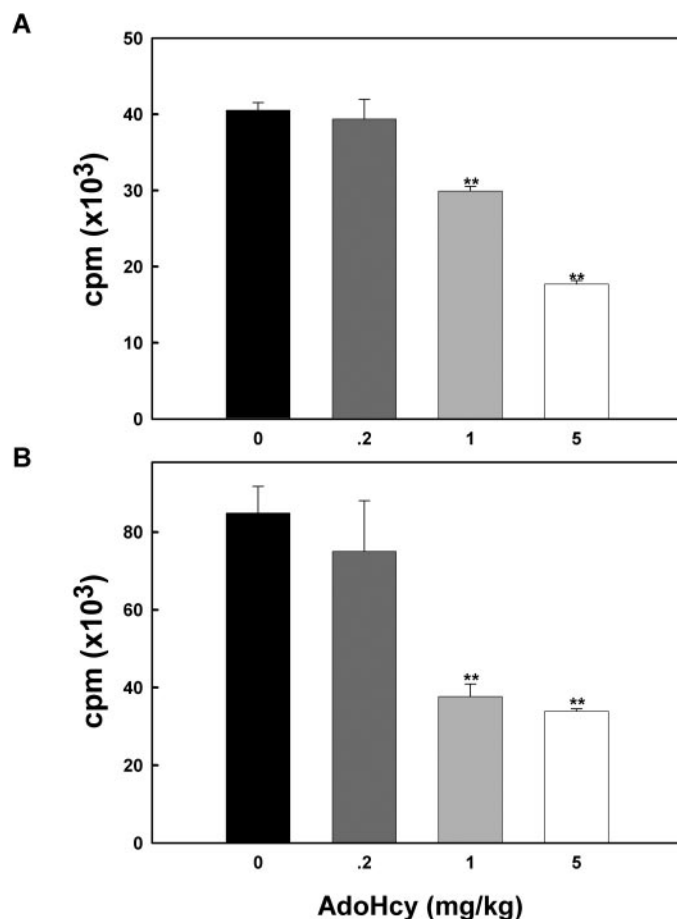


Fig. 5. Administration of AdoHcy inhibits OVA-induced splenocyte (A) and LN cell (B) proliferation. OVA-immunized mice were treated with AdoHcy at 0.2, 1, and 5 mg/kg/day by i.p. injection. On day 21 postimmunization, splenocytes and draining LN cells were recovered and 5×10^5 cells were incubated with 100 μ g/ml OVA for 72 h. Cultures were pulsed with 0.5 μ Ci/well of [^{3} H]thymidine for the final 12 h. Results are expressed as mean $\pm$ S.E.M. of eight mice. **, $P < 0.01$ compared with vehicle control (Dunnett's test). Two separate experiments were performed with similar results.

responses. This study provides evidence that DZ2002 may be an effective pharmaceutical agent in the prevention of antigen-specific immune responses and probably exerts its immunosuppressive effects by increasing intracellular AdoHcy levels, thus blocking cellular transmethyations.

An increasing number of people throughout the world are affected by autoimmune diseases with very limited therapeutic options. These diseases are associated with humoral or cell-mediated immune responses against one or more of the body's own self-determinants (Lernmark, 2001). Blockade of immune responses to self-antigens that contribute to disease has remained an elusive and challenging problem. We and others, however, have recently established that AdoHcy hydrolase inhibitors are effective in the treatment of several immune-mediated disease animal models, including DNFB-induced delayed-type hypersensitivity reactions (Saso et al., 2001; Wu et al., 2005) and collagen-induced arthritis (Wolos et al., 1993c). This study demonstrated that like other AdoHcy hydrolase inhibitors, DZ2002 effectively suppressed immune responses to OVA. Supporting our data, Wolos et al. (1993b) reported previously that a different AdoHcy hydrolase inhibitor, MDL 28,842, also suppressed OVA-induced

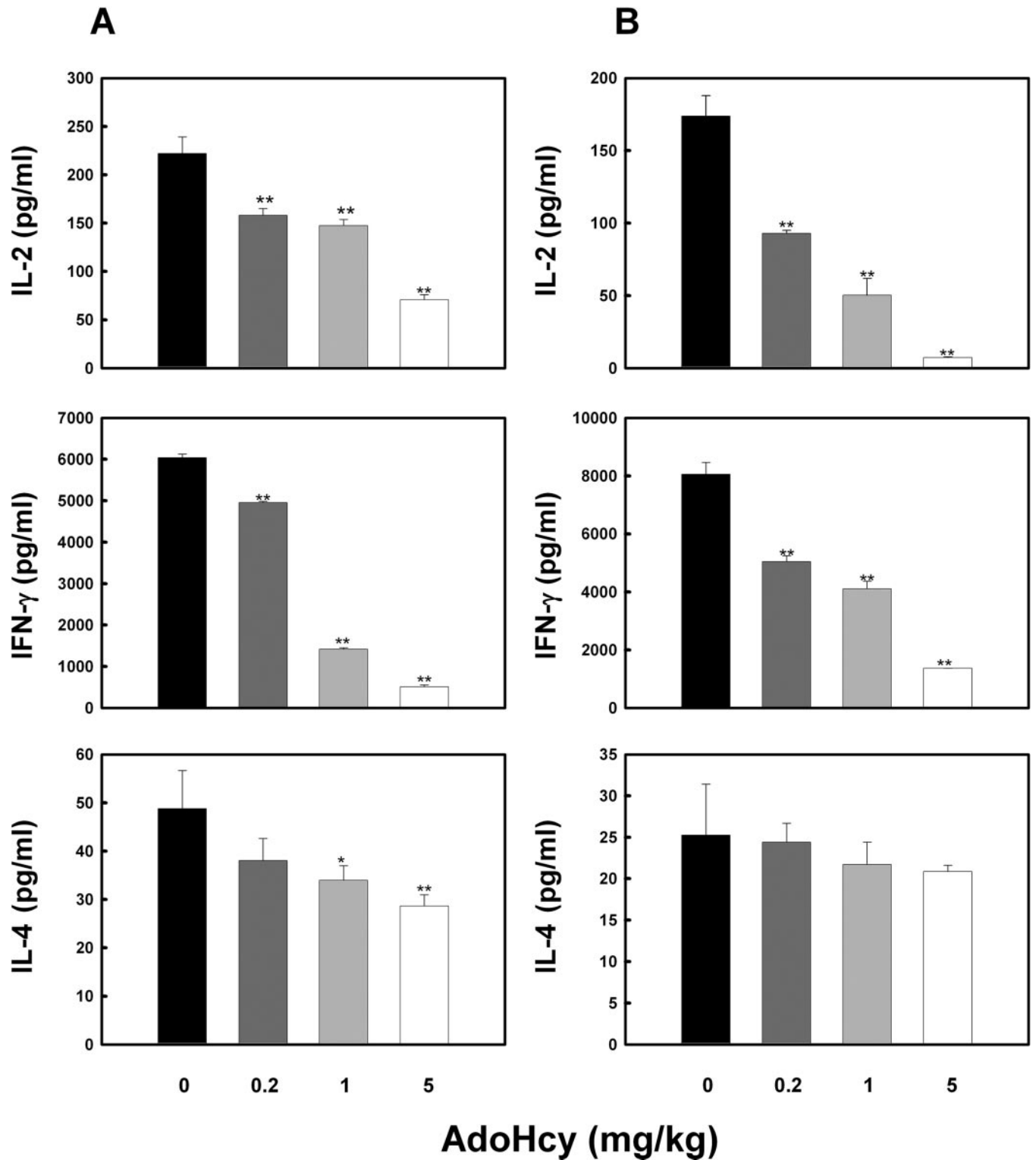


Fig. 6. Administration of AdoHcy inhibits OVA-induced splenocyte (A) and LN cell (B) cytokine production. OVA-immunized mice were treated with AdoHcy at 0.2, 1, and 5 mg/kg/day by i.p. injection. On day 21 postimmunization, splenocytes and draining LN cells were recovered and 5×10^5 cells were incubated for 48 h with 100 μ g/ml OVA. Culture supernatants were collected and analyzed by ELISA for levels of IL-2, IL-4, and IFN- γ . Results are expressed as mean $\pm$ S.E.M. of eight mice. *, $P < 0.05$; **, $P < 0.01$ compared with vehicle control (Dunnett's test). Two separate experiments were performed with similar results.

LN cell proliferation in mice (Wolos et al., 1993b). In combination with our data, these results indicated that AdoHcy hydrolase blockers possess inhibitory properties for antigen-specific immune responses that may play crucial roles in the

pathogenesis of autoimmune diseases and should therefore be further evaluated as possible pharmaceutical agents in the prevention and/or treatment of autoimmune diseases.

Nonetheless, it should be mentioned that we previously

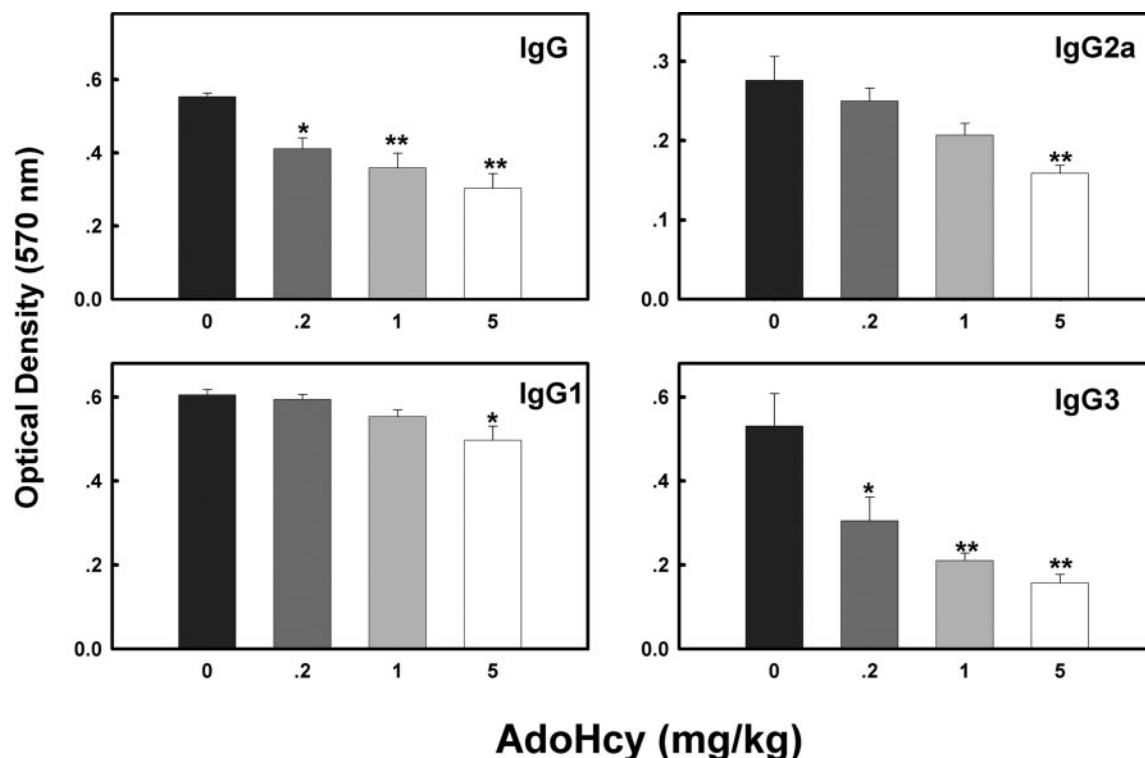


Fig. 7. Administration of AdoHcy reduces production of anti-OVA IgG antibody and its subclasses. OVA-immunized mice were treated with AdoHcy at 0.2, 1, and 5 mg/kg/day by i.p. injection. On day 21 postimmunization, anti-OVA IgG, IgG1, IgG2a, and IgG3 levels were determined by ELISA. Results are expressed as mean $\pm$ S.E.M. of six mice. *, $P < 0.05$; **, $P < 0.01$ compared with vehicle control (Dunnett's test). Two separate experiments were performed with similar results.

documented an inhibitory effect of DZ2002 on in vitro macrophage function, and on delayed-type hypersensitivity responses, which although primarily initiated by $CD4^+$ T cells, also require macrophage recruitment (Wu et al., 2005). Based on the above-mentioned data, and our experiments presented here, we cannot rule out that during the single immunization with OVA, the antigen presentation capacity of macrophages and dendritic cells was similarly altered. Logically, decreased antigen presentation cell activity would therefore lead to the development of fewer T cells, resulting in a smaller OVA-responding T cell compartment showing decreased overall proliferative capacity and cytokine production in response to OVA. Consequently, direct inhibition of T cell function and/or decreased antigen presentation cell activity are probably dual mechanism(s) responsible for the in vivo inhibitory effect of DZ2002 and are currently being further studied in autoimmune animal models.

It has long been recognized that antigen-specific IgG antibody production is T cell-dependent. Previous studies with the AdoHcy hydrolase inhibitor MDL 28,842 demonstrated decreased levels of OVA-specific IgG (Wolos et al., 1993b). Consistent with that report, the present study also demonstrates that DZ2002 suppresses anti-OVA IgG production. The reductions in anti-OVA antibody production by inhibition of the AdoHcy hydrolase is probably explained by blockade of antigen-specific lymphocyte activation. In fact, we recently demonstrated that DZ2002 suppressed immune responses to sheep red blood cells, indicating that DZ2002 also has an effect on antibody-secreting B cells (Wu et al., 2005). It is therefore likely that AdoHcy hydrolase inhibitors also suppress T and B cell activation/function.

Naive $CD4^+$ T cells primarily differentiate into one of two effector phenotypes, Th1 or Th2 cells. Th1 cells primarily produce IL-2, IFN- γ , and TNF- α , whereas Th2 cells primarily produce IL-4, IL-5, IL-6, IL-10, and IL-13 (Seder and Paul, 1994; Theofilopoulos and Lawson, 1999). Previously, Wolos et al. (1993b) reported that MDL 28,842 reduced in vitro IL-2 production by T cells after mitogen stimulation (Wolos et al., 1993b). In the present study, we demonstrated that DZ2002 treatment significantly decreased production of Th1-associated cytokines such as IL-2 and IFN- γ , but IL-4, a Th2-type cytokine, was also reduced in response to OVA. Interestingly, decreases in IL-2 and IFN- γ were more significant than reductions seen in IL-4. Moreover, DZ2002 administration significantly suppressed the production of Th1-associated IgG subclasses such as IgG2a and IgG3. Although a reduction in the Th2-associated subclass IgG1 was also noted in DZ2002-treated mice, decreases in IgG2a and IgG3 seemed to be greater than those seen in IgG1. Since IgG2a, IgG3, and IgG1 production are dependent on Th1 and Th2 cells (Isakson et al., 1982; Burstein and Abbas, 1993), respectively, these results suggest that DZ2002 may preferentially inhibit Th1-driven immune responses compared with Th2 immune responses after OVA immunization. Previous reports have established that several factors, such as the strain of animal, dose of antigen, route of injection, and use of adjuvants may contribute to the preferential induction of Th1 or Th2 responses (Abbas et al., 1996). In our experiment, vehicle-treated C57BL/6 mice immunized subcutaneously with OVA mixed with complete Freund's adjuvant had less abundant IL-4-producing T cells and enhanced IFN- γ production, that is, a relatively Th1-skewed response. That the Th1-associated re-

sponses seemed more sensitive to DZ2002 than Th2-type responses may be related to the factors mentioned above.

DZ2002, selected out of hundreds of analogs, is a very potent inhibitor of AdoHcy hydrolase with an optimal K_i of ~ 17.9 nM (Wu et al., 2005). The present study demonstrated that, in vivo, DZ2002 treatment substantially inhibited splenic AdoHcy hydrolase activity. As predicted, intracellular AdoHcy levels in spleens of DZ2002-treated animals were significantly elevated compared with controls.

Next, we investigated whether the methylation inhibitor AdoHcy affected antigen-specific immune responses in OVA-immunized mice. Previous reports have shown that AdoHcy can be found intracellularly in both the spleen and liver after i.p. administration (Gharib et al., 1985). We found that, indeed, similar to DZ2002, in vivo treatment with AdoHcy suppressed OVA-specific immune responses. More recently, others demonstrated that a known methylase inhibitor, 5'-methylthioadenosine, decreased IL-2, IL-4, and IFN- γ gene expression in T lymphocytes (Mowen et al., 2004; Richard et al., 2005). Together, these results provide evidence that the suppressive effect of DZ2002 on antigen-specific immune responses is probably related to the elevation of endogenous AdoHcy.

It is known that high levels of AdoHcy can block phosphatidylinositol kinase, an enzyme responsible for second messenger signaling in cellular activation (Pike and DeMeester, 1988). Since T cell activation via the T cell receptor uses the phosphatidylinositol signaling pathway (Desai et al., 1990), inhibition of phosphatidylinositol kinase would probably inhibit T cell activation. Alternatively, eukaryotic mRNA contains a transmethylation-dependent methylated 5'-cap structure that may prevent protein degradation by phosphatases and ribonucleases (Konarska et al., 1984). Methylation is also required by certain cell membrane signal transduction molecules (Mowen et al., 2004; Richard et al., 2005). In these proteins, methylation is required for the protein to translocate to its correct site in the cell membrane (Tan et al., 1991). Therefore, reductions in transmethylation by AdoHcy may lead to increased degradation and/or decreased translation of message, thus preventing the proper expression and function of receptors required for optimal lymphocyte activation and cytokine production. Any one or combination of these mechanism(s) could be responsible for the inhibitory effect seen with DZ2002 and certainly warrant further study.

In conclusion, the present study demonstrated that the AdoHcy hydrolase inhibitor DZ2002 suppressed antigen-specific immune responses, especially Th1-associated responses, and that the inhibitory effect of DZ2002 is probably related to the elevation of endogenous AdoHcy. Therefore, we think that the data warrant further evaluation of DZ2002 as a potential therapeutic agent for immune-mediated diseases with a Th1-type bias, such as multiple sclerosis.

Acknowledgments

We thank Dr. Chong Yuan for helpful experimental discussions.

References

- Abbas AK, Murphy KM, and Sher A (1996) Functional diversity of helper T lymphocytes. *Nature (Lond)* **383**:787–793.
- Boger RH, Bode-Boger SM, Sydow K, Heistad DD, and Lentz SR (2000a) Plasma concentration of asymmetric dimethylarginine, an endogenous inhibitor of nitric oxide synthase, is elevated in monkeys with hyperhomocyst(e)inemia or hypercholesterolemia. *Arterioscler Thromb Vasc Biol* **20**:1557–1564.
- Boger RH, Sydow K, Borlak J, Thum T, Lenzen H, Schubert B, Tsikas D, and Bode-Boger SM (2000b) LDL cholesterol upregulates synthesis of asymmetrical dimethylarginine in human endothelial cells: involvement of S-adenosylmethionine-dependent methyltransferases. *Circ Res* **87**:99–105.
- Burstein HJ and Abbas AK (1993) In vivo role of interleukin 4 in T cell tolerance induced by aqueous protein antigen. *J Exp Med* **177**:457–463.
- Desai DM, Newton ME, Kadlecik T, and Weiss A (1990) Stimulation of the phosphatidylinositol pathway can induce T-cell activation. *Nature (Lond)* **348**:66–69.
- Feng YH, Zhou WL, Wu QL, Li XY, Zhao WM, and Zou JP (2002) Low dose of resveratrol enhanced immune response of mice. *Acta Pharmacol Sin* **23**:893–897.
- Fonlupt P, Roche M, Cronenberg L, and Pacheco H (1979a) Action of S-adenosyl-L-homocysteine on the metabolism of dopamine, norepinephrine and serotonin in rat brain. *Arch Int Pharmacodyn Ther* **240**:35–44.
- Fonlupt P, Roche M, Cronenberg L, and Pacheco H (1979b) Activation by S-adenosylhomocysteine of norepinephrine and serotonin in vitro uptake in synaptosomal preparations from rat brain. *Experientia* **35**:1089–1090.
- Fu YF, Xiong Y, and Guo Z (2005) A reduction of endogenous asymmetric dimethylarginine contributes to the effect of captopril on endothelial dysfunction induced by homocysteine in rats. *Eur J Pharmacol* **508**:167–175.
- German DC, Bloch CA, and Kredich NM (1983) Measurements of S-adenosylmethionine and L-homocysteine metabolism in cultured human lymphoid cells. *J Biol Chem* **258**:10997–11003.
- Gharib A, Sarda N, Chabannes B, and Pacheco H (1985) Pharmacokinetics and metabolism of S-adenosyl-L-homocysteine, in rats and dog. *Eur J Drug Metab Pharmacokin* **10**:289–291.
- Isakson PC, Pure E, Vitetta ES, and Krammer PH (1982) T cell-derived B cell differentiation factor(s). Effect on the isotype switch of murine B cells. *J Exp Med* **155**:734–748.
- Konarska MM, Padgett RA, and Sharp PA (1984) Recognition of cap structure in splicing in vitro of mRNA precursors. *Cell* **38**:731–736.
- Lernmark A (2001) Series introduction: autoimmune diseases: are markers ready for prediction? *J Clin Invest* **108**:1091–1096.
- Mowen KA, Schurter BT, Fathman JW, David M, and Glimcher LH (2004) Arginine methylation of NIP45 modulates cytokine gene expression in effector T lymphocytes. *Mol Cell* **15**:559–571.
- Pike MC and DeMeester CA (1988) Inhibition of phosphoinositide metabolism in human polymorphonuclear leukocytes by S-adenosylhomocysteine. *J Biol Chem* **263**:3592–3599.
- Richard S, Morel M, and Cleroux P (2005) Arginine methylation regulates IL-2 gene expression: a role for PRMT5. *Biochem J* **388**:379–386.
- Saso Y, Conner EM, Teegarden BR, and Yuan CS (2001) S-Adenosyl-L-homocysteine hydrolase inhibitor mediates immunosuppressive effects in vivo: suppression of delayed type hypersensitivity ear swelling and peptidoglycan polysaccharide-induced arthritis. *J Pharmacol Exp Ther* **296**:106–112.
- Seder RA and Paul WE (1994) Acquisition of lymphokine-producing phenotype by CD4⁺ T cells. *Annu Rev Immunol* **12**:635–673.
- She QB, Nagao I, Hayakawa T, and Tsuge H (1994) A simple HPLC method for the determination of S-adenosylmethionine and S-adenosylhomocysteine in rat tissues: the effect of vitamin B6 deficiency on these concentrations in rat liver. *Biochem Biophys Res Commun* **205**:1748–1754.
- Tan EW, Perez-Sala D, Canada FJ, and Rando RR (1991) Identifying the recognition unit for G protein methylation. *J Biol Chem* **266**:10719–10722.
- Theofilopoulos AN and Lawson BR (1999) Tumour necrosis factor and other cytokines in murine lupus. *Ann Rheum Dis* **58**:49–51.
- Wang W, Kramer PM, Yang S, Pereira MA, and Tao L (2001) Reversed-phase high-performance liquid chromatography procedure for the simultaneous determination of S-adenosyl-L-methionine and S-adenosyl-L-homocysteine in mouse liver and the effect of methionine on their concentrations. *J Chromatogr B Biomed Sci Appl* **762**:59–65.
- Wolos JA, Frondorf KA, Babcock GF, Stripp SA, and Bowlin TL (1993a) Immunomodulation by an inhibitor of S-adenosyl-L-homocysteine hydrolase: inhibition of in vitro and in vivo allogeneic responses. *Cell Immunol* **149**:402–408.
- Wolos JA, Frondorf KA, Davis GF, Jarvi ET, McCarthy JR, and Bowlin TL (1993b) Selective inhibition of T cell activation by an inhibitor of S-adenosyl-L-homocysteine hydrolase. *J Immunol* **150**:3264–3273.
- Wolos JA, Frondorf KA, and Esser RE (1993c) Immunosuppression mediated by an inhibitor of S-adenosyl-L-homocysteine hydrolase. Prevention and treatment of collagen-induced arthritis. *J Immunol* **151**:526–534.
- Wu QL, Fu YF, Zhou WL, Wang JX, Feng YH, Liu J, Xu JY, He PL, Zhou R, Tang W, et al. (2005) Inhibition of S-adenosyl-L-homocysteine hydrolase induces immunosuppression. *J Pharmacol Exp Ther* **313**:705–711.
- Yoshino S, Yamaki K, Li X, Sai T, Yanagisawa R, Takano H, Taneda S, Hayashi H, and Mori Y (2004) Prenatal exposure to bisphenol A up-regulates immune responses, including T helper 1 and T helper 2 responses, in mice. *Immunology* **112**:489–495.
- Yoshino S, Yamaki K, Yanagisawa R, Takano H, Hayashi H, and Mori Y (2003) Effects of bisphenol A on antigen-specific antibody production, proliferative responses of lymphoid cells and TH1 and TH2 immune responses in mice. *Br J Pharmacol* **138**:1271–1276.
- Yuan CS, Liu S, Wnuk SF, Robins MJ, and Borchardt RT (1994) Mechanism of inactivation of S-adenosylhomocysteine hydrolase by (E)-5',6'-didehydro-6'-deoxy-6'-halohomoadenosines. *Biochemistry* **33**:3758–3765.
- Yuan CS, Saso Y, Lazarides E, Borchardt RT, and Robins MJ (1999) Recent advances in S-adenosyl-L-homocysteine hydrolase inhibitors and their potential clinical applications. *Exp Opin Ther Patents* **9**:1197–1206.

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