Nasal Administration Of Glutamate Decarboxylase (GAD65) Peptides Induces Th2 Responses and Prevents Murine Insulin-dependent Diabetes

By Jide Tian,* Mark A. Atkinson,§ Michael Clare-Salzler,§ Alan Herschenfeld,* Thomas Forsthuber,‖ Paul V. Lehmann,‖ and Daniel L. Kaufman**

From the *Department of Molecular and Medical Pharmacology, Brain Research and Molecular Biology Institute, University of California, Los Angeles, California 90095-1735; ‡Department of Pathology, University of Florida, Gainesville, Florida 32610; and ‖Department of Pathology, Case Western Reserve University, Cleveland, Ohio 44106

Summary

We previously demonstrated that a spontaneous Th1 response against glutamate decarboxylase (GAD65) arises in NOD mice at four weeks in age and subsequently T cell autoimmunity spreads both intramolecularly and intermolecularly. Induction of passive tolerance to GAD65, through the inactivation of reactive T cells before the onset of autoimmunity, prevented determinant spreading and the development of insulin-dependent diabetes mellitus (IDDM). Here, we examined whether an alternative strategy, designed to induce active tolerance via the engagement of Th2 immune responses to GAD65, before the spontaneous onset of autoimmunity, could inhibit the cascade of Th1 responses that lead to IDDM. We observed that a single intranasal administration of GAD65 peptides to 2-3-wk-old NOD mice induced high levels of IgG1 antibodies to GAD65. GAD65 peptide treated mice displayed greatly reduced IFNγ responses and increased IL-5 responses to GAD65, confirming the diversion of the spontaneous GAD65 Th1 response toward a Th2 phenotype. Consistent with the induction of an active tolerance mechanism, splenic CD4+ (but not CD8+) T cells from GAD65 peptide-treated mice, inhibited the adoptive transfer of IDDM to NOD-scid/scid mice. This active mechanism not only inhibited the development of proliferative T cell responses to GAD65, it also limited the expansion of autoreactive T cell responses to other β cell antigens (i.e., determinant spreading). Finally, GAD65 peptide treatment reduced insulitis and long-term IDDM incidence. Collectively, these data suggest that the nasal administration of GAD65 peptides induces a Th2 cell response that inhibits the spontaneous development of autoreactive Th1 responses and the progression of β cell autoimmunity in NOD mice.

We previously demonstrated in non-obese diabetic (NOD) mice that autoreactive Th1 cell responses develop spontaneously and gradually spread both intramolecularly and intermolecularly, creating a cascade of responses that ultimately destroys the insulin-secreting β cells and results in insulin-dependent diabetes mellitus (IDDM) (1). Autoantigen based therapies offer the opportunity to prevent, or inhibit, this amplificatory cascade through mechanisms that are minimally invasive. There are two basic autoantigen-based immunotherapeutic strategies. The first strategy, passive tolerance, aims to inactivate, or prevent the priming of autoreactive T cells by presenting antigen without appropriate costimulatory signals, or by interfering with the formation of MHC/TCR complexes through peptide antagonists or monoclonal antibodies (reviewed in references 2 and 3). Therapies based on passive tolerance are highly specific, but require detailed knowledge of the target antigens, the effector TCR, or the peptide/MHC complex they recognize. Therefore, passive tolerance has almost exclusively been used to prevent experimentally induced autoimmune disease, in which the initiating autoantigen is defined.

We demonstrated the efficacy of passive tolerance to prevent spontaneous β cell autoimmunity in NOD mice by identifying GAD65 as the earliest known T cell target antigen and demonstrating that inactivation of GAD65-
reactive T cells (by the intravenous administration of GAD65), before the loss of self-tolerance, prevented the development of β cell autoimmunity (1). The GAD65 treated mice did not have detectable levels of GAD65 autoantibodies and their splenic T cells failed to protect recipients in adoptive transfer experiments, consistent with the induction of passive tolerance (J. Tian and D.L. Kaufman, unpublished observations).

The second immunotherapeutic strategy involves administering autoantigens in modes that induce protective immune responses, creating active forms of self-tolerance (3–8). This approach does not require knowledge of the initial target antigen and its protective effect may not be confined only to the administered autoantigen, as the activated immune responses may downregulate effector T cells through “bystander” suppression (4). A recently favored mechanism for active tolerance involves the induction of Th2 cells that protect a target tissue via the local release of cytokines that downregulate Th1 cells (9–12). However, evidence demonstrating the protective effects of Th2 cells in autoimmune disease has been largely confined to experimentally induced diseases (4). In the case of IDDM, Th2 cells have in fact been suggested to be both nonprotective and nondiabetogenic in adoptive transfer experiments (13).

We reasoned that if inactivation of Th1 responses to GAD65 before the onset of autoimmunity prevents β cell autoimmunity in NOD mice, the early priming of a Th2 response to GAD65 could also interfere with diabetogenesis—either by diverting the pool of GAD65-reactive precursor T cells from developing toward a Th1 phenotype, or by downregulating effector T cells in the target organ via bystander suppression. It is not known however, what effect the induction of Th2 responses to an autoantigen, before the spontaneous development of pathogenic Th1 responses to that autoantigen, would have on determinant spreading and disease progression. Moreover, it is unclear what modes of antigen administration would induce Th2 responses, whereas antigens are easily delivered to mucosal surfaces, this treatment has been recently reported to induce a variety of T cell responses (i.e., peripheral deletion, anergy, and activation of CD4+ and CD8+ cells, references 4, 6, 14–16). Here, we show in NOD mice, that a single nasal administration of GAD65 peptides, before the onset of autoimmunity, induces a Th2 cell response that actively diverts/downregulates the development of autoreactive Th1 responses and inhibits autoimmune disease progression.

Materials and Methods

Mice. NOD mice (Taconic Farms Inc., Germantown, NY) were bred under SPF conditions. Only female NOD mice were used in this study. Insulinitis begins at 4 wk and the average age of disease onset in females is at 22 wk. Approximately 80% of the female mice display IDDM by 30 wk in age. IDDM increases to ~90% by 40 wk in age and remains stable thereafter.

Antigens. We previously characterized in NOD mice the development of T cell autoreactivity to a panel of overlapping GAD65 peptides that span the molecule (1). We administered a mixture of the synthetic peptides that contain the earliest GAD65 T cell target determinants (peptides 17, 34, 35, and 36, references 1 and 17), or a control GAD65 peptide that does not contain a T cell target determinant (peptide 11 in references 1 and 17). These peptides, as well as the hsp65 immunodominant peptide (18) were prepared as previously described (17). To avoid confusion between the experimental GAD65 peptides (peptides 17, 34, 35, 36) that contain T cell determinants and the control GAD65 peptide (peptide 11) which does not, we refer to peptide 11 as the “control” peptide. Mouse GAD65 (19) and control Escherichia coli β-galactosidase, used in T cell proliferation assays, were purified as previously described (1). Human GAD65, used in ELISA assays for autoantibodies, was provided by Synetics Biotechnology (Stockholm, Sweden). Bovine insulin B chain was from Sigma Chemical Co. (St. Louis, MO). Hen egg white lysozyme peptide (HEL1–25), which contains a dominant determinant, was provided by Eli Sercarz.

Treatment. Female NOD mice at 2–3 wk were given a single intranasal dose of a mixture of four GAD65 peptides (peptides 17, 34, 35, 36, 50 μg of each in 50 μl PBS). Control NOD mice received a single dose of the control peptide (200 μg in 50 μl PBS). Mice received peptides while under light ether anesthesia using a thin drawn-out plastic tube (inserted 5–10 mm intranasally) attached to a Hamilton syringe. At 12 wk, some mice were killed to characterize splenic T cell responses and insulin. The remaining mice were followed up to 1 yr to determine the effect of treatment on long-term IDDM frequency. Urine glucose levels were monitored weekly for diabetes by Tes-tape. After observing abnormal glucose in the urine, blood glucose levels were monitored twice weekly. Two consecutive blood glucose levels >13 mmol/L were considered as IDDM onset.

GAD65 Autoantibody Assays. GAD65 (10 μg/ml) was bound to 96-well plates (Nunc) in 0.1 M NaHCO3, pH 8.5, at 4°C overnight. The wells were rinsed with PBS and then blocked with 3% BSA in PBS for 1 h. Mouse sera was added (0.1 ml of a 1/50 dilution) and incubated 1 h at 37°C. Following washing, bound Ig was characterized using affinity-purified HRP-coupled goat anti-mouse IgG + A + M (H+L) (Pierce Chem.), or HRP-coupled goat anti-mouse isotype-specific antibodies for IgG1, IgG2a, IgM (Southern Biotech Associates) and 2,2'-azo-bis(3-ethylbenzothiazoline-6-sulfonic acid) (Sigma Chemical Co.). Sera from untreated BALB/c and AKR mice were used as negative controls.

Cytokine Assays. Spleen cells were plated at 8 × 106 cells/ml in 24-well microtiter plates as previously described (1). GAD65 or β-galactosidase were present at 100 μg/ml. After 48 h, culture supernatants were analyzed by lymphokine-specific ELISA. For the IFNγ ELISA, mAb R4-6A2 was used as the capturing agent and XMG 1.2-biotin (PharMingen). For IL-5 detection, mAb TRFK5 and TRFK4-biotin (PharMingen) were used. The concentration of lymphokines was determined by comparison with a standard curve of recombinant murine IFNγ or IL-5 (PharMingen).

Adaptive Transfer of Diabetes. Ten million splenic mononuclear cells from untreated-diabetic mice were mixed with an equal number of splenic mononuclear cells from (18–20 wk old) experimental or control peptide treated mice, and the mixture injected i.v. into 10-wk-old NOD-scid/scid mice (20). A positive control group received 1 × 107 splenic mononuclear cells obtained from only untreated diabetic mice.

To examine the T cell subset that conferred protection from the adoptive transfer of disease, CD4+ and CD8+ splenic T cell populations were isolated from 5-wk-old control and GAD65...
peptide–treated mice (3 wk after treatment) using T cell and CD4+ and CD8+ enrichment columns (R&D Systems, Minneapolis, MN). Three-color FACS® analysis using PE-anti-CD3, Cy-chrome-anti-CD4+, and FITC-anti-CD8+ antibodies (PharMingen) showed that the negatively selected CD4+ subset contained less than 1% CD8+ T cells, and that the CD8+ subset contained less than 3% CD4+ T cells. 5 x 10^6 purified T cell subsets from control or GAD65 peptide treated mice were mixed with 10^7 splenic mononuclear cells from diabetic NOD mice and injected i.v. into NOD-scid/scid mice.

**Results**

**Nasal Administration of GAD65 Determinants Induces GAD65-specific Autoantibodies of the IgG1 Isotype.** Experimental and control NOD mice were given a single intranasal dose of peptides at 2–3 wk and humoral responses to GAD65 were tested at 12 wk. We observed that NOD mice treated with the control peptide had low levels of GAD65 autoantibodies (Fig. 1), similar to that observed in unmanipulated age-matched NOD mice, and only slightly greater than that found in BALB/c and AKR mice (data not shown). However, high levels of GAD65 autoantibodies were observed in most of the GAD65 peptide–treated NOD mice, indicating that the treatment triggered a T cell–dependent anti-GAD65 B cell response. To identify the type of T cell that provided help for GAD65 autoantibody production, we characterized the isotype of the anti-GAD65 immunoglobins. The GAD65 autoantibodies in the GAD65 peptide–treated group were almost exclusively of the IgG1 subclass (Fig. 1), which is indicative of a Th2 response (22, 23). In contrast, IgG2a GAD65 autoantibodies, which require Th1 help, were at very low levels in both the experimental and control groups. These data suggest that nasal administration of GAD65 peptides activates a GAD65-specific Th2 response.

**T Cells from GAD65 Peptide Treated Mice Display Decreased IFNγ and Increased IL-5 Production in Response to GAD65.** We previously demonstrated that unmanipulated NOD mice at 12 wk have a clonally expanded, CD4+ L-selectin−, IFNγ-secreting population of GAD65–specific T cells, (i.e., a Th1 response to GAD65, reference 1). Consistent with our previous findings, we observed that T cells from 12 wk old control peptide–treated NOD mice secreted high levels of IFNγ in response to GAD65 challenge in vitro (Fig. 2). In contrast, T cells from GAD65 peptide–treated NOD mice displayed greatly reduced IFNγ responses. Further-
more, while IL-5 secretion was almost undetectable in the control group, clear IL-5 responses were detectable in some mice of the experimental group, confirming the activation of Th2 responses.

Adoptive Cotransfer of Splenic T Cells from GAD65 Peptide-treated Mice Protects Recipient NOD-scid/scid Mice from IDDM. We next examined whether T cells from GAD65 peptide-treated NOD mice could actively inhibit the adoptive transfer of diabetes. Splenic mononuclear cells from mice treated with GAD65 or control peptides were cotransferred with T cells from diabetic NOD mice to NOD-scid/scid mice. All of the positive control mice that received cells from unmanipulated diabetic NOD mice, and 90% of the mice that received a mixture of cells from unmanipulated diabetic and control peptide-treated NOD mice, became diabetic within 5 wk after transfer (Fig. 3a). In contrast, only 20% (n = 10) of the NOD-scid/scid mice that received a mixture of cells from GAD65 determinant treated mice and unmanipulated diabetic mice developed IDDM (P < 0.01). Those recipients that did develop IDDM showed a delayed onset of disease relative to the control groups.

To examine the T cell subset that inhibited disease development, splenic CD4+ and CD8+ T cell populations were isolated from the spleens of control or GAD65 peptide-treated mice and cotransferred with mononuclear cells from diabetic NOD mice into NOD-scid/scid mice. Mice that received CD4+ or CD8+ T cells from control peptide-treated mice progressed to IDDM within 4 wk (Fig. 3b). In contrast, the CD4+, but not the CD8+, T cell population of the GAD65 peptide-treated mice conferred protection from the adoptive transfer of disease, at a level similar to that of unfractionated T cells from these mice. These
data demonstrate that the nasal administration of GAD65 peptides can induce potent CD4+ regulatory cells that suppress the adoptive transfer of IDDM.

**The Nasal Administration of Key GAD65 Peptides Reduces Insulitis and IDDM Incidence.** Examination of the pancreata from 12-wk-old control and experimental mice revealed that all islets had infiltrating lymphocytes at levels essentially identical to those observed in unmanipulated NOD mice (1). In contrast, nearly all of the NOD mice treated with peptides containing GAD65 target determinants failed to display significant proliferative responses to GAD65 (Fig. 4). Furthermore, none of the mice in the experimental group displayed significant proliferative responses to hsp65 or the B chain of insulin. Thus, the nasal administration of GAD65 determinants inhibited the intermolecular spreading of the autoreactive Th1 responses that naturally occur in NOD mice.

**The Nasal Administration of Key GAD65 Peptides Reduces Th2 Immune Response and IDDM Incidence.** Examination of the pancreata from 12-wk-old control mice revealed that all islets had infiltrating lymphocytes at levels essentially identical to those observed in unmanipulated NOD mice (1). In contrast, nearly all of the NOD mice treated with peptides containing GAD65 target determinants failed to display significant proliferative responses to GAD65 (Fig. 4). Furthermore, none of the mice in the experimental group displayed significant proliferative responses to hsp65 or the B chain of insulin. Thus, the nasal administration of GAD65 determinants inhibited the intermolecular spreading of the autoreactive Th1 responses that naturally occur in NOD mice.

The mechanism by which the induction of Th2 responses interferes with disease progression may involve one, or several, of the following: (a) the induction of Th2 responses before the spontaneous priming of Th1 responses may have driven a limited number of uncommitted, or not fully differentiated, Th0 cells toward a Th2 lineage; (b) the...
first generation of Th2 cells may have migrated to the target organ where their local secretion of cytokines may have downregulated antigen presentation in the islets (25, 26), thereby limiting the amplificatory cascade of Th1 responses; (c) alternatively, the local release of cytokines by Th2 cells may have upregulated islet antigen presentation, which in the absence of appropriate costimulatory factors, caused the antigen-specific T cells that engaged these determinants to be anergized or deleted (27); or (d) the upregulation of islet antigen presentation may have caused T cell priming that was Th2 biased due to the IL-4 environment that was established by the first wave of Th2 cells, creating an amplificatory cascade of Th2 responses; (e) The GAD-specific Th2 response may have locally downregulated Th1 cells through the secretion of cytokines such as IL-10 and IL-4 (bystander suppression, references 4, 10, 11, 22).

Th2 cells are generally thought to exert protective functions in experimental models of autoimmune disease (3, 4, 9, 15) and administration of IL-4 and IL-10 are anti-inflammatory (24, 28). However, two recent reports question whether Th2 cells exert anti-inflammatory functions. Katz et al. showed that Th2 cells fail to mitigate β cell destruction when coinfected with Th1 cells in adoptive transfer experiments (13). Our conflicting findings may be due to differences in the nature and frequency of the autoantigen-reactive T cells used in our experiments. Katz et al. simultaneously injected clonal populations of preactivated β cell–specific Th1 and Th2 cells. Under these conditions it is likely that Th2 cell secreted cytokines could not exert regulatory functions before Th1 cells engaged target determinants. We injected a mixed population of unactivated spleen cells, in which the frequency of GAD65-reactive T cells was ~1 in 10^4–10^5. Our protocol may not have flooded the target organ with an autoreactive Th1 component, thus providing an opportunity for Th2 cells to exert protective functions. These experiments also targeted different β cell antigens, whereas our protocol induced GAD65-specific Th2 cells, the T cell populations used by Katz et al. have an unknown specificity.

Apparently also contradicting the protective Th2 cell hypothesis, is the finding that IDDM is accelerated in transgenic mice expressing IL-10 in their β cells (29). However, IL-10 may have complex functions. For example, IL-10 is a growth factor for CTL and facilitates their priming (30, 31). Since CD8+ cells are involved in the pathogenesis of IDDM in NOD mice (32, 33), the IL-10 produced in the transgenic islets may have promoted an anti-β cell CD8+ response and accelerated disease progression. It is also possible that other cytokines such as IL-4 and IL-13 mediate the anti-inflammatory functions of Th2 cells. Thus, these two reports do not disprove a protective role for Th2 cells. To the contrary, our data substantiate the contention that Th2 cells can serve a protective role.

In conclusion, we have shown that a single nasal administration of peptides containing T cell target determinants can induce antigen-specific Th2 responses and inhibit the spontaneous cascade of events that lead to IDDM. Thus the inhalation of autoantigen peptides may provide an easily administered, minimally invasive, immunotherapy to prevent spontaneous autoimmune disease.

We would like to thank Eli Sercarz, Mitchell Kronenberg, Chris Evans, and Allan Tobin for their help and advice.

This work was supported by grants from the National Institutes of Health (D.L. Kaufman), the American Diabetes Association (D.L. Kaufman), and the Juvenile Diabetes Foundation International (P.V. Lehmann and J. Tian).

Address correspondence to Daniel L. Kaufman, Department of Molecular and Medical Pharmacology, University of California, Los Angeles, CA 90095-1735.

Received for publication 18 October 1995 and in revised form 12 February 1996.

References

sponses to house dust mite allergen by inhalation of the dominant T cell epitope in naive and sensitized mice. J. Exp. Med. 178:1783–1788.