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Peptide-MHC Class II Dimers as Therapeutics to Modulate Antigen-Specific T Cell Responses in Autoimmune Diabetes

Emma L. Masteller,* Matthew R. Warner,* Walter Ferlin,† Valeria Judkowski,‡ Darcy Wilson,‡ Nicolas Glaichenhaus,† and Jeffrey A. Bluestone2*†

Type 1 diabetes is an autoimmune disorder caused by autoreactive T cells that mediate destruction of insulin-producing β cells of the pancreas. Studies have shown that T cell tolerance can be restored by inducing a partial or altered signal through the TCR.

To investigate the potential of bivalent peptide-MHC class II/Ig fusion proteins as therapeutics to restore Ag-specific tolerance, we have developed soluble peptide I-Ag7 dimers for use in the nonobese diabetic mouse model of diabetes. I-Ag7 dimers with a linked peptide specific for islet-reactive BDC2.5 TCR transgenic CD4+ T cells were shown to specifically bind BDC2.5 T cells as well as a small population of Ag-specific T cells in nonobese diabetic mice. In vivo treatment with BDC2.5 peptide I-Ag7 dimers protected mice from diabetes mediated by the adoptive transfer of diabetogenic BDC2.5 CD4+ T cells. The dimer therapy resulted in the activation and increased cell death of transferred BDC2.5 CD4+ T cells. Surviving cells were hypoproliferative to challenge by Ag and produced increased levels of IL-10 and decreased levels of IFN-γ compared with cells from control I-Ag7 dimer-treated mice. Anti-IL-10R therapy reversed the tolerogenic effects of the dimer. Thus, peptide I-Ag7 dimers induce tolerance of BDC2.5 TCR T cells through a combination of the induction of clonal anergy and anti-inflammatory cytokines. The Journal of Immunology, 2003, 171: 5587–5595.

Type 1 diabetes is caused by autoreactive T cells that mediate the destruction of insulin-producing β cells of the pancreas. Therapeutic approaches designed to prevent or cure the disease through general immune suppression, such as treatments with cyclosporin A, anti-inflammatory cytokines, or Abs against proinflammatory cytokines or T cells, have been shown to be effective in animal models and, in some cases, human clinical trials, but also have a variety of undesirable side effects (1, 2). Thus, approaches that could selectively tolerize autoreactive T cells without disrupting the ability of the immune system to neutralize opportunistic pathogens would be highly advantageous.

T cell tolerance can be achieved by inducing a partial or altered signal through the TCR/CD3 complex using Abs or altered peptide ligands (3, 4). Treatment of mice with anti-CD3 mAbs that have been altered to prevent binding to FcR prevents or reverses diabetes (5–7). Non-FcR-binding anti-CD3 mAbs were found to induce cell death and anergy in Th1 cells, which are associated with pathogenesis of diabetes while promoting survival/expansion of Th2 (8), and CD4+CD25+ regulatory T cells (9), which are associated with protection from disease. Based on the success in animal models, clinical trials were initiated using a humanized non-FcR-binding anti-CD3 mAb to treat patients with new-onset type 1 diabetes (10). A single course of anti-CD3 mAb treatment was found to arrest the deterioration of insulin production in the majority of treated patients. Anti-CD3 mAb treatment resulted in a transient reduction in the number of circulating lymphocytes and in detectable presence of IL-10 in the serum. Thus, the effect of anti-CD3 treatment may have been to shift the autoimmune response toward the production of protective or regulatory cytokines.

Recently, soluble ligands for TCRs have been developed to target Ag-specific T cells (11–13). These TCR ligands consist of engineered MHC molecules in multimeric form, some with covalently attached peptide Ags. Like mAbs directed against the TCR/CD3 complex, soluble bivalent peptide-MHC molecules are capable of delivering a signal through the TCR (14–17). These reagents may therefore provide for therapy to selectively induce tolerance in Ag-specific T cells involved in autoimmune responses. Recently, peptide-MHC multimers have been shown to be effective in delaying the onset and reducing the severity of collagen-induced arthritis in mice by induction of Ag-specific hyporesponsivity (18). Furthermore, soluble peptide-MHC has been shown to be effective in treating diabetes in mice using a model double-transgenic system in which mice express the influenza virus hemagglutinin (HA) in pancreatic islets and a HA-specific TCR (19). However, these studies did not address the effect of peptide-MHC therapy in spontaneous autoimmune systems with naturally occurring Ags or in the presence of a diverse repertoire of autoreactive T cells.

To investigate the potential of peptide-MHC class II multimers in treating autoimmune diabetes, we have generated I-Ag7 dimers with covalently linked BDC2.5 mimotope peptides that are capable of identifying BDC2.5 TCR transgenic CD4+ T cells and BDC2.5 mimotope-peptide-reactive cells from nonobese diabetic (NOD) mice. The BDC2.5 CD4+ T cell clone originally isolated from a diabetic NOD mouse is highly diabetogenic when transferred into young NOD recipients (20). Transgenic NOD mice expressing the TCR α (Vα1)- and β (Vβ4)-chains of the BDC2.5 T cell clone

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3 Abbreviations used in this paper: HA, hemagglutinin; HEL, hen egg lysozyme; NOD, nonobese diabetic; Tg, transgene.
PEPTIDE-MHC CLASS II DIMERS MODULATE AUTOACTIVE T CELLS

Materials and Methods

Mice

NOD mice were obtained from Taconic (Germantown, NY). NOD.BDC2.5 TCR transgenic mice (24) were obtained from D. Mathis (Harvard, Boston, MA). In our colony, <10% of the BDC2.5 TCR transgenic mice become diabetic unless bred into a T cell-deficient setting. NOD.TCRα-deficient mice were obtained from D. Serreze (The Jackson Laboratory, Bar Harbor, ME). All animals were bred and maintained under specific pathogen-free conditions at the University of California animal facility and treated in accordance with University of California animal care guidelines.

Peptides

Peptides were produced by the University of California Biomolecular Resource Center or the University of California HHMI Protein Facility. OVA peptide(323-339) consisted of amino acids ISQAVHAAHAEINEAGR. Other peptides with acetylated N termini and amide C termini included: 1040–31, YVRPLWVRLME, specific for BDC2.5 T cells (23); and hen egg lysozyme(11–25), HEL). AMKRHGLDNYRRGSY. In our experience, the N-acetylation of the peptides resulted in increased activity of the peptides, as measured in T cell proliferation assays.

Production of soluble bivalent peptide I-Aβ7/IgG2a fusion molecules and multimeric staining reagents

Constructs encoding the I-Aα α- and I-Aβ β-chains fused to acidic/basic leucine zipper sequences with the I-Aα acidic leucine zipper further fused to the Fc portion of mouse IgG2a were based on those previously published by Malherbe et al. (25). This template was used for introducing DNA combinations of the conformation-specific anti-I-Aβ7 mAbs, 10-2.16 (provided by A. Sant, University of Rochester, Rochester, NY), and a mAb against the IgG2a Fc portion. Peptide I-Aβ7 dimers were purified over affinity columns using protein A (Life Technologies, Rockville, MD). Bound molecules were eluted using 0.1 M sodium citrate (pH 4.5). Fractions were neutralized with the addition of 2 M Tris (pH 9.0), dialyzed against PBS, and concentrated using Centricon concentrators (Millipore, Bedford, MA).

Construction of BDC2.5 TCR transgenic mice

BDC2.5 TCR transgenic T cells were identified (22); however, by screening peptide libraries, several highly active decapetides that stimulate BDC2.5 transgenic T cells were identified (23). In vivo administration of BDC2.5 mimotope I-Aβ7 dimers prevented the onset of diabetes in mice receiving activated BDC2.5 TCR transgenic spleen cells. Treatment with BDC2.5 mimotope I-Aβ7 dimers resulted in activation and increased cell death of the autoreactive T cells. More interestingly, the remaining autoreactive T cells became hypoproliferative to subsequent challenge to Ag and preferentially produced the anti-inflammatory cytokine, IL-10. Treatment of NOD mice with BDC2.5 mimotope I-Aβ7 dimers resulted in the increased production of IL-10 upon rechallenge with Ag in vitro. More significantly, anti-IL-10R mAb reversed the tolerogenic effects of the dimer in vivo. In contrast, BDC2.5 mimotope peptide I-Aβ7 dimers failed to prevent diabetes induced by the transfer of spleen cells from diabetic NOD mice or reverse diabetes in diabetic NOD mice. These results suggest that peptide-MHC class II multimers may serve as therapeutics to modulate Ag-specific T cell responses in autoimmune disease by inducing selective T cell anergy and deviating the residual autoimmune response toward production of anti-inflammatory cytokines, but that targeting a single specificity may be insufficient to treat diabetes in naturally occurring settings.

Production of HEL cell line

A 5-wk-old NOD mouse was immunized with 20 µg of HEL(11–25) peptide in CFA in a hind footpad and in the hind flanks. Seven days later, draining lymph nodes were harvested and processed into single cell suspensions. Cells were restimulated in vitro with 1 µM HEL peptide in the presence of irradiated NOD spleen cells in DMEM with standard supplements and 5% FCS. After the second round of in vitro stimulation, IL-2 was added to 20 U/ml. The specificity of the HEL line was demonstrated in T cell proliferation assays (data not shown).

T cell proliferation and responsiveness assays

For T cell proliferation assays using immobilized I-Aβ7 dimers, flat-bottom 96-well plates were coated with rat anti-mouse IgG2a (BD PharMingen or Southern Biotechnology Associates, Birmingham, AL) in PBS by overnight incubation at 4°C and washed with PBS. Purified peptide I-Aβ7 dimers at 2 µg/ml were added in 100 µl/well, incubated overnight at 4°C, and washed with PBS. BDC2.5 CD4+ T cells were enriched from spleen and lymph nodes to 95–98% purity by negative sorting with magnetic beads (Miltenyi Biotec, Auburn, CA). BDC2.5 T cells or the HEL T cell line were added at 5 × 10^6 cells/well along with anti-CD28 mAb PV-1 at 1 µg/ml. [H]Thymidine at 1 µCi/well was added during the last 8 h of a 48-h culture; cells were harvested onto glass fiber filters; and incorporated radioactivity was quantified in a beta scintillation counter (Topcount; PerkinElmer Life Sciences, Boston, MA).

Flow cytometry and fluorescence-activated cell sorting

For general detection of Ag-specific T cells, 1 × 10^6 spleen, peripheral lymph node cells, or T cells from T cell lines were incubated with 2.4G2 anti-Flc mAb supernatant, followed by incubation with peptide I-Aβ7/Ala-exa 488 protein A complexes for 1 h on ice in PBS supplemented with 2% BSA and 0.05% sodium azide. PerCP or APC-conjugated anti-CD4 mAbs (BD PharMingen) were added during the last 30 min. Cells were then washed and analyzed on a FACSCalibur (BD Immunocytometry Systems, San Jose, CA). For cell-sorting experiments and decreased background staining in detection of rare cells in nontransgenic NODs, CD4+ T cells were first enriched using negative selection by magnetic bead separation (Miltenyi Biotec). Cells at 1 × 10^6/ml were stained with peptide I-Aβ7 multimers at 100 µg/ml in PBS with 2% FCS for 1 h on ice. APC-conjugated anti-CD4 mAbs were added during the last 30 min. CyChrome-conjugated anti-CD8 and anti-B220 (BD PharMingen), Tri-color-conjugated anti-F4/80, biotin-conjugated anti-mouse NK cells (Catag, Burlingame, CA), followed by CyChrome-conjugated streptavidin and Via-Probe (BD PharMingen) were also added during the last 30 min. Cells staining positive for these non-CD4+ T cell reagents were excluded from analysis.

For analysis of adoptively transferred BDC2.5 T cells, the additional mAbs were: FITC anti-Vβ4, PE anti-CD25, and PE CD62L (BD PharMingen). Annexin V-PE staining was performed following manufacturer’s recommendations (Southern Biotechnology Associates). Nonviable cells were excluded using Via-Probe (BD PharMingen).

In vitro expansion of 1040-31-reactive cells from NOD mice

CD4+ T cells were enriched from spleen and lymph nodes by negative sorting using magnetic cell sorting. A total of 2 × 10^6 CD4+-enriched cells was incubated with 5 × 10^6 irradiated NOD spleen cells in 24-well plates in the presence of 10 µM 1040-31 peptide. After 6 days, cells were pooled, separated by Ficoll-Hypaque to remove dead cells, and stained for 1040-31- or OVA-reactive T cells.
Adoptive transfer experiments and treatment of mice with peptide I-A^\text{g7} dimers

Whole spleen cells from 5- to 10-wk-old BDC2.5 TCR transgenic mice were transferred with 0.1 \mu M 1040-31 peptide for 5 days. On day 5, 1 x 10^6 cells were injected i.v. into cohorts of TCR-\alpha-deficient NOD mice 5–12 wk of age. Twenty-four hours following injection of activated BDC2.5 spleen cells, mice were injected retro-orbitally with PBS or 10 \mu g per injection of the indicated peptide I-A^\text{g7} dimers. Mice received either a single series of three to four injections during the first 3–4 days following the initial transfer of BDC2.5 spleen cells or a single series of injections, followed by weekly injections of the indicated dimers at 10 \mu g per injection. Anti-IL-10R mAb 1B1.2 (provided by L. Chatenoud, Centre de l’Association Claude Bernard sur les Maladies Autoinimmunes et Hopital Necker Enfants Malades Institut Fédératif de Recherche Necker-Enfants-Malades, Paris, France) or control rat Ig (BW6) was given i.p. at a dose of 0.5 mg on days 1, 3, 5, and 7 after the transfer of BDC2.5 T cells. Glucose levels were determined from tail vein blood samples using Lifescan (One touch II; Lifescan, Milpitas, CA) glucose meters. Mice were considered diabetic after two consecutive measurements over 250 mg/dl.

Analysis of cytokine production by ELISA and intracellular cytokine staining

Total spleen or pancreatic lymph node cells from adoptively transferred recipient mice were stimulated in vitro with 0.1 \mu M 1040-31 peptide for 24 or 48 h, and cytokine levels were measured by ELISA using reagents purchased from Endogen (Cambridge, MA) and BD PharMingen. For intracellular cytokine staining, cells were treated with PMA (10 ng/ml), ionomycin (0.5 \mu M), and monensin (3 \mu M) for 3–4 h. Cells were harvested and stained with APC-conjugated anti-CD4 (BD PharMingen) and either p31 I-A^\text{g7}/Alexa 488-protein A multimers or FITC-conjugated anti-V\beta4 (BD PharMingen). Cells were fixed with 2% paraformaldehyde, permeabilized with 0.1% saponin, and stained with the indicated PE-conjugated mAbs (BD PharMingen).

Results

Production and characterization of peptide I-A^\text{g7} dimers

To study islet-reactive T cells, we produced dimers of soluble peptide I-A^\text{g7} in which the BDC2.5 mimotope peptide 1040-31 (23) was covalently linked to the N terminus of the I-A^\text{g7} \beta-chain (hereafter referred to as p31 I-A^\text{g7} dimers). A control dimer was also produced with HEL peptide (aa 11–25) covalently attached (HEL I-A^\text{g7}). The transmembrane and cytoplasmic domains of the I-A^\text{d} \alpha- and the I-A^\text{g7} \beta-chains were replaced with leucine zipper dimerization domains to produce soluble molecules and to promote assembly of the \alpha- and \beta-chains. The \alpha-chain was further modified by the addition of the murine IgG2a Fc domain allowing for the production of divalent molecules, as previously described (25). I-A^\text{g7} dimers were produced in stably transfected Drosophila S2 cells and purified by affinity chromatography.

Peptide I-A^\text{g7} multimers were examined for the ability to identify Ag-specific T cells in flow cytometry assays. Peptide I-A^\text{g7} dimers were preincubated with Alexa 488-coupled protein A to enhance flow cytometric staining (25). p31 I-A^\text{g7} multimers stained \sim 95% of CD4^+ T cells from BDC2.5 transgenic (Tg^+) NOD mice (Fig. 1A), comparable to the number of BDC2.5 Tg^+ T cells identified by an Ab to V\beta4 (data not shown). p31 I-A^\text{g7} multimers stained relatively low numbers of CD4^+ T cells from a HEL-specific NOD T cell line (1.7%). In contrast, HEL I-A^\text{g7} dimers stained \sim 18% of CD4^+ T cells from the HEL line, but detected relatively low numbers of CD4^+ cells from BDC2.5 Tg^+ mice (0.7%).

In addition to dimers with covalently linked peptides, empty I-A^\text{g7} dimers capable of being loaded with various peptides in vitro were generated. Empty I-A^\text{g7} reagents were demonstrated to be functional in flow cytometry experiments. Empty I-A^\text{g7} multimers did not react with CD4^+ T cells from either NOD or BDC2.5 TCR transgenic mice (0.8 and 1.5%, respectively); however; empty I-A^\text{g7} multimers loaded with the 1040-31 peptide stained 94% of BDC2.5 CD4^+ T cells. There was no readily apparent increase in staining of NOD CD4^+ T cells (1.1%) as compared with background with this reagent (Fig. 1B).

Peptide I-A^\text{g7} dimers were also tested for biological activity and specificity in T cell proliferation assays using CD4^+ T cells isolated from BDC2.5 transgenic NOD mice and the HEL-specific T cell line. Peptide I-A^\text{g7} dimers were immobilized in 96-well plates, and T cell proliferation was measured by [\text{3H}]thymidine incorporation following 48 h of culture. p31 I-A^\text{g7} dimers activated BDC2.5 Tg^+ T cells, but failed to activate the HEL line above background levels (Fig. 1C). Similar activation of BDC2.5 T cells was observed with empty I-A^\text{g7} dimers loaded with 1040-31, but not control peptides (data not shown). In contrast, HEL I-A^\text{g7} dimers activated the HEL line, but failed to activate BDC2.5 Tg^+ T cells. Empty unloaded I-A^\text{g7} dimers failed to activate either population of T cells. The addition of Con A did not induce activation.
Treatment with p31 I-A<sup>e7</sup> dimers prevents diabetes induced by BDC2.5 Tg<sup>+</sup> cells

To investigate the therapeutic potential of p31 I-A<sup>e7</sup> dimers on the development of diabetes, we used an adoptive transfer model with activated BDC2.5 Tg<sup>+</sup> T cells. In this model, BDC2.5 T cells were activated in vitro with 0.1 μM 1040-31 peptide for 5 days. One million cells were then transferred i.v. to TCR-α-deficient NOD mice. Recipient mice rapidly developed diabetes within 6–10 days following transfer of islet-reactive cells (Fig. 2, A and B). Twenty-four hours after the transfer of activated BDC2.5 spleen cells, recipient mice were treated with three daily injections of PBS or 10 μg of p31 I-A<sup>e7</sup>, empty I-A<sup>e7</sup>, or HEL I-A<sup>e7</sup> dimers. Mice treated with PBS, empty I-A<sup>e7</sup> dimers, or HEL I-A<sup>e7</sup> dimers showed no delay in the onset of diabetes, becoming diabetic 6–8 days following transfer (Fig. 2, A and B). In contrast, mice receiving a single series of treatments with p31 I-A<sup>e7</sup> dimers showed delayed onset of diabetes, with mice remaining normoglycemic until around 21 days after the initial transfer of cells (Fig. 2A). Control mice that were injected with equal molar quantities of soluble 1040-31 peptide corresponding to that carried by 10 μg of dimer did not show any delay in the onset of diabetes, suggesting that protection was not occurring through presentation of the 1040-31 peptide on endogenous APCs (data not shown). Weekly treatment with p31 I-A<sup>e7</sup> dimers was found to further enhance protection from diabetes. All mice receiving weekly treatment with p31 I-A<sup>e7</sup> dimers were protected from the onset of diabetes throughout the course of treatment (Fig. 2B). Histology at days 8–9 following transfer of activated T cells revealed that the degree and severity of insulitis were reduced in mice receiving treatments of p31 I-A<sup>e7</sup> dimers, as shown by the lower frequency of infiltrated islets and the higher frequency of noninfiltrated islets and peri-insulitis compared with that seen in control-treated mice, which showed massive infiltration of all islets at this time point (data not shown).

In vivo treatment with p31 I-A<sup>e7</sup> dimers induced T cell hyporesponsiveness

Immune suppression/tolerance can be achieved by several mechanisms including prevention of TCR engagement by down-regulating or blocking the TCR, depletion of autoreactive T cells, or the induction of anergy. To determine how p31 I-A<sup>e7</sup> dimers were preventing the onset of diabetes, recipient mice were analyzed 3 days following transfer. At this time point, mice had received two injections of peptide-MHC dimers or PBS, and all groups of mice were normoglycemic. Compared with control-treated mice, p31 I-A<sup>e7</sup> dimer-treated animals showed slight increases in the numbers of BDC2.5 Tg<sup>+</sup> CD4<sup>+</sup> T cells found in the spleens and pancreatic lymph nodes. BDC2.5 Tg<sup>+</sup> CD4<sup>+</sup> cells in p31 I-A<sup>e7</sup> dimer-treated mice ranged from 1 × 10<sup>5</sup> to 6 × 10<sup>5</sup>, averaging 3.4 × 10<sup>5</sup> in the spleen, and ranged from 0.3 × 10<sup>5</sup> to 2.6 × 10<sup>5</sup>, averaging 1.4 × 10<sup>5</sup> in the pancreatic lymph nodes. Total BDC2.5 Tg<sup>+</sup> CD4<sup>+</sup> cells in control-treated mice ranged from 1 × 10<sup>5</sup> to 2.8 × 10<sup>5</sup>, averaging 1.5 × 10<sup>5</sup> in the spleens, and ranged from 0.26 × 10<sup>5</sup> to 1 × 10<sup>5</sup>, averaging 0.61 × 10<sup>5</sup> in the pancreatic lymph nodes. There were no significant differences in cell numbers between control PBS-treated and control I-A<sup>e7</sup> dimer-treated animals. In p31 I-A<sup>e7</sup> dimer-treated mice, a minor percentage of BDC2.5 Tg<sup>+</sup> T cells appeared to have down-regulated their TCR; however, the majority of cells retained expression of TCR, as determined by both p31 I-A<sup>e7</sup> dimer and anti-V<sub>β</sub>4 Ab staining (data not shown). At day 3 following transfer, BDC2.5 CD4<sup>+</sup> T cells in p31 I-A<sup>e7</sup> dimer-treated mice were activated in both the spleen and pancreatic lymph nodes, as determined by increased CD25 and CD69 expression and decreased CD62L expression compared with BDC2.5 Tg<sup>+</sup> CD4<sup>+</sup> cells isolated from PBS or control dimer-treated mice (Fig. 3A). BDC2.5 CD4<sup>+</sup> cells from p31 I-A<sup>e7</sup> dimer-treated mice also showed an increase in cell size consistent with an activated phenotype (data not shown). At this time point, transferred BDC2.5 CD4<sup>+</sup> cells in PBS or control I-A<sup>e7</sup> dimer-treated animals appeared to be resting in the spleen based on low levels of CD25 and CD69 expression. Transferred cells in the pancreatic lymph nodes of these animals expressed CD69 consistent with studies demonstrating that BDC2.5 Tg<sup>+</sup> CD4<sup>+</sup> cells encounter cognate Ag in pancreatic lymph nodes (26), but in contrast to cells recovered from pancreatic lymph nodes of p31 I-A<sup>e7</sup> dimer-treated mice, expressed lower levels of CD25 and had not fully down-regulated CD62L (Fig. 3A).

The increase in the activation phenotype of transferred cells in the p31 I-A<sup>e7</sup> dimer-treated animals was accompanied by an increase in cell death. At day 3 following transfer, BDC2.5 CD4<sup>+</sup> cells from spleen and pancreatic lymph nodes of p31 I-A<sup>e7</sup> dimer treated showed a greater percentage of cells staining positive for annexin V compared with cells from control-treated mice (Fig. 3B). However, the increased cell death did not result in total deletion of BDC2.5 CD4<sup>+</sup> cells. By days 8–10, the numbers of BDC2.5 CD4<sup>+</sup> cells had increased in both the spleen and pancreatic lymph nodes of p31 I-A<sup>e7</sup> dimer-protected animals, averaging...
Treatment with p31 I-Aε7 dimers activates autoreactive T cells and results in increased cell death. A. Pancreatic lymph node cells from mice treated with HEL or p31 I-Aε7 dimers were stained with anti-CD4, anti-Vβ4 (to identify BDC2.5 Tg+ cells), and either anti-CD25 or anti-CD62L mAbs. Data shown are staining of CD4+/Vβ4+ gated cells. Similar results were found when using p31 I-Aε7 multimers in place of anti-Vβ4 mAbs to identify BDC2.5 transgenic T cells. B. Pancreatic lymph node cells from treated mice were stained with annexin V and anti-CD4 and anti-Vβ4 mAbs. Data shown are staining of CD4+/Vβ4+, 7-amino actinomycin D− cells.

6.7 × 10^6 (±5.1 × 10^6) in the spleens and averaging 1.0 × 10^5 (±1.3 × 10^5) in the pancreatic lymph nodes. Unlike the early time points, the cells that were observed late did not appear to have an activated phenotype in that CD25 expression was negative (data not shown). At these later time points, the number of transferred cells in control-treated animals averaged 1.7 × 10^6 (±1.4 × 10^6) in the spleens and 2.2 × 10^5 (±1.7 × 10^5) in the pancreatic lymph nodes.

To examine whether BDC2.5 CD4+ cells in p31 I-Aε7 dimer-treated animals were responsive to Ag, the ex vivo response of transferred BDC2.5 cells to 1040-31 peptide was tested. Compared with equal numbers of BDC2.5 Tg+ CD4+ cells from control-treated mice, cells from the spleen and pancreatic lymph nodes from p31 I-Aε7 dimer-treated mice showed reduced proliferative responses to peptide (Fig. 4, A and B). Responsiveness could not be restored by the addition of IL-2.

**Treatment with p31 I-Aε7 dimers generates IL-10-producing cells**

Suppression/Tolerance of autoimmunity can also be achieved by deviating the immune response from a pathogenic Th1 response to a nonpathogenic or regulatory response. To investigate the effect of p31 I-Aε7 dimer treatment on cytokine production, splenic cells from treated animals were stimulated in vitro with 1040-31 peptide at the indicated concentrations for spleen cells and at 100 nM for pancreatic lymph node cells with or without IL-2 (10 U/ml). Proliferation was measured by [3H]thymidine incorporation. Data shown are representative of three independent experiments.

There was little difference in IL-2 production between the different groups of mice. The increased production of IL-4 and IL-10 from p31 I-Aε7 dimer-treated mice was confirmed by intracellular cytokine staining with a greater percentage of these cells from both spleen and pancreatic lymph nodes staining for IL-4 and IL-10 compared with cells from PBS and control I-Aε7 dimer-treated mice (Fig. 5B and data not shown).

To determine whether IL-10 was involved in the suppression of diabetes mediated by p31 I-Aε7 dimer treatment in vivo, blocking anti-IL-10R mAb or control rat Ig mAb was administered to mice receiving activated BDC2.5 transgenic spleen cells and treatment with p31 I-Aε7 dimers. Anti-IL-10R mAb blocked the protective effect of p31 I-Aε7 dimer treatment, with mice becoming diabetic at the same rate as mice receiving control or no dimer treatment (Fig. 5C). Control Ig had no effect on p31 I-Aε7 dimer protection.

**Detection of BDC2.5 mimotope-reactive cells in wild-type NOD mice**

Having determined that peptide I-Aε7 dimer therapy was successful in preventing diabetes in a system in which the majority of T cells expressed a single TCR, we next wanted to test the effect of peptide-MHC class II multimer therapy in the more complex wild-type NOD background. Because the BDC2.5 mimotope 1040-31 was identified from a combinatorial peptide library and searches of databases revealed no precise matches (23), we first wanted to be sure that the p31 I-Aε7 dimers were able to target Ag-specific cells from a nontransgenic NOD background. NOD mice were immunized with 1040-31 or control OVA peptide (aa 323–339) emulsified in CFA, and CD4+ cells from draining lymph nodes were analyzed for the presence of Ag-specific T cells. For the detection of rare cells, samples were also stained for B220, CD8, F4/80, and CD4. The resulting supernatants were analyzed by ELISA.
CD11c. Cells staining positive for these reagents were excluded from analysis, resulting in decreased background staining (compare background levels in Fig. 1A vs Fig. 6A). FACS analysis of draining lymph nodes detected an increase in the number of p31-reactive CD4$^+$/H11001H11006$^+$ T cells in p31-injected mice with numbers representing 0.34$\pm$0.02% of CD4$^+$ cells compared with levels of 0.04$\pm$0.02% in nonimmunized mice and 0.11$\pm$0.02% in mice immunized with OVA peptide (Fig. 6A). Conversely, OVA-loaded I-A$^d$ dimers detected a population of cells representing 0.21$\pm$0.01% of CD4$^+$ cells in OVA-immunized mice compared with 0.05$\pm$0.01% in nonimmunized mice and 0.06$\pm$0.01% in p31-immunized mice. Moreover, in vitro restimulation of cells from peptide-primed mice with immunizing peptide resulted in increased percentages of peptide-specific cells detected by peptide I-A$^d$ dimers. After one round of in vitro stimulation, the percentage of CD4$^{high}$ cells detected by p31 I-A$^d$ dimers increased to 24% in 1040-31 peptide-stimulated cells (data not shown). The percentage of CD4$^{high}$ cells detected by OVA-loaded I-A$^d$ dimers increased to 12% in OVA peptide-stimulated cells.

To further substantiate that 1040-31-reactive CD4$^+$ cells identified by p31 I-A$^d$ dimers by flow cytometry were indeed specific for 1040-31 peptide, dimer-positive and dimer-negative CD4$^+$ T cells from immunized mice were sorted ex vivo using FACS and then tested for reactivity to 1040-31 presented by APCs or to plate-bound p31 I-A$^d$ dimers. p31 I-A$^d$ dimer-positive, but not dimer-negative, CD4$^+$ T cells showed 1040-31 reactivity, indicating that peptide-specific cells were identified by peptide I-A$^d$ dimers.

FIGURE 5. Treatment with p31 I-A$^d$ dimers results in increased production of IL-10 and decreased production of IFN-γ. A. Splenic cells from HEL and p31 I-A$^d$-treated mice were stimulated in vitro with 1040-31 peptide (100 nM). Cytokine levels were measured by ELISA. Data shown are means $\pm$ SD of six replicates from two mice and are representative of three independent experiments. B. Spleen cells from HEL and p31 I-A$^d$-treated mice were treated with PMA, ionomycin, and monensin for 4 h in vitro. Cells were stained for V$\beta$4, CD4, and the indicated cytokine, as outlined in Materials and Methods, and analyzed by flow cytometry. Data shown are staining for CD4$^+$V$\beta$4$^+$ cells. C. Adoptive transfer of activated BDC2.5 spleen cells and treatment with p31 I-A$^d$ dimer, as outlined in Fig. 2A. Mice were treated on days 1, 3, 5, and 7 with 0.5 mg of either anti-IL-10R mAb or control mAb, as indicated.

FIGURE 6. BDC2.5 mimotope-peptide p31 I-A$^d$ dimers detect 1040-31-reactive cells from NOD mice. A. NOD mice were primed with either the BDC2.5 mimotope peptide 1040-31 or OVA peptide in CFA. Seven days later, draining lymph nodes were isolated and stained with anti-CD4 mAbs and either p31 I-A$^d$ multimers or OVA-loaded I-A$^d$ multimers. Samples were also stained with anti-B220, anti-CD28, anti-F4/80, and CD11c. Cells staining positive for these Ags were excluded from analysis, resulting in decreased background staining. Representative FACS tracings from a single experiment are shown. The average percentages of dimer$^+$ cells $\pm$ SD calculated from three independent experiments are indicated. B. FACS was used to sort p31 I-A$^d$ dimer$^+$ and dimer$^-$ cells from 1040-31/CFA-primed animals. Sorted populations were challenged with either OVA peptide or 1040-31 peptide presented by irradiated NOD APCs, and proliferation was measured by [3H]thymidine incorporation. C. CD4$^+$ cells were enriched from spleens and lymph nodes of NOD mice. Cells were stimulated in vitro with 1040-31 peptide (10$^{-8}$ M) presented by irradiated NOD APCs. After 6 days, cells were pooled and live cells were collected on a Ficoll gradient and stained as indicated in Fig. 2A. Data shown are the percentage of either p31 I-A$^d$ dimer$^+$ or OVA-loaded I-A$^d$ dimer$^-$ cells found in the CD4$^{high}$ population. Results shown are representative of two independent experiments. In the second experiment, 0.15% of p31 I-A$^d$ dimer-reactive cells were detected compared with 0.07% detected with control.
negative cells proliferated in response to 1040-31 peptide presented by NOD APCs (Fig. 6B). Furthermore, only p31 I-A$^\alpha$-dimer-positive cells were reactive to plate-bound recombinant p31 I-A$^\alpha$ (data not shown). These data demonstrated that cells capable of responding to 1040-31 exist in the NOD repertoire and that p31 I-A$^\alpha$-dimers could detect most, if not all, 1040-31-reactive cells from immunized mice.

T cells from prediabetic and diabetic NODs respond to BDC2.5 mimotope peptides, 1040-63 and 1040-31, suggesting that BDC2.5 mimotope-reactive T cells have undergone a spontaneous expansion stimulated by self Ag in vivo (23) (data not shown). To determine whether p31 I-A$^\alpha$-dimer treatment had any effect on BDC2.5 mimotope-reactive cells in NOD mice, spleen cells from treated animals were challenged in vitro with 1040-31 peptide and analyzed by flow cytometry. This approach has been shown to enhance detection of rare cells by peptide-MHC class II multimers by expanding the pool of preexisting Ag-specific cells (27–29). Flow cytometry analysis of CD4$^{\text{high}}$ T cell populations from NOD mice stimulated with 1040-31 peptide showed an increase in the percentage of p31 I-A$^\alpha$-reactive cells, increasing to 0.22% from 0.04 ± 0.02% detected in unprimed NOD T cells (Fig. 6, A and C). In contrast, CD4$^{\text{high}}$ cells reactive to OVA I-A$^\beta$ remained at approximately the same percentage in 1040-31-stimulated cells compared with freshly isolated T cells, 0.08% vs 0.05 ± 0.01%, respectively (Fig. 6, A and C).

**Effect of BDC2.5 mimotope I-A$^\alpha$ dimers on endogenous BDC2.5 mimotope-reactive cells in NOD mice**

To determine whether p31 I-A$^\alpha$ dimer treatment had any effect on endogenous 1040-31 peptide-reactive cells, NOD mice were treated with p31 or HEL I-A$^\alpha$ dimers. Spleen cells from treated mice were then challenged with 1040-31 or HEL peptide in vitro. IL-10 and IFN-γ were below detection in both groups upon challenge with HEL peptide (Fig. 7A). IL-10 was also undetectable in HEL I-A$^\alpha$ dimer-treated cells in response to 1040-31 peptide. In contrast, IL-10 was detectable in p31 I-A$^\alpha$-dimer-treated cells upon response to 1040-31 peptide. IFN-γ production in response to 1040-31 challenge was not decreased in cells from p31 I-A$^\alpha$-dimer-treated animals compared with cells from control-treated mice (Fig. 7A). Treatment with p31 I-A$^\alpha$ did not result in cells becoming anergic to Ag as spleen cells from p31 I-A$^\alpha$-dimer-treated mice proliferated as well or better than cells from control-treated animals (Fig. 7B). Furthermore, treatment with p31 I-A$^\alpha$ dimers failed to prevent diabetes induced by the transfer of spleen cells from diabetic mice and failed to reverse diabetes in newly diabetic NOD mice (data not shown).

**Discussion**

We have developed peptide I-A$^\alpha$ dimers for use in the NOD model of autoimmune diabetes to explore the properties of peptide-MHC class II dimers as therapeutics to selectively inhibit the pathogenicity of diabetogenic T cells. We initially characterized the tolerogenic capabilities of peptide-MHC class II dimers on a previously primed autoimmune response using BDC2.5 TCR transgenic T cells. In vivo treatment with BDC2.5 mimotope-peptide-pulsed p31 I-A$^\alpha$ dimers prevented diabetes caused by transferred BDC2.5 T cells. Treatment with p31 I-A$^\alpha$ dimers resulted in the activation of transferred CD4$^+$ T cells in both the pancreatic lymph nodes and the spleen, as determined by the increased expression of the activation markers CD25 and CD69 and the decrease in CD62L expression. Activation was accompanied by an increase in cell death, as determined by annexin V staining. An abortive form of activation that results in apoptosis has been described previously as a mechanism for inducing peripheral tolerance for both naive and memory cells (30, 31). p31 I-A$^\alpha$-dimer-induced activation and death of autoreactive T cells are also consistent with other studies of peptide-MHC class II multimers in which a soluble dimeric DR2-IgG fusion protein with a bound peptide from myelin basic protein was found to anergize a myelin basic protein-specific T cell clone through initial activation, followed by susceptibility to late stage apoptosis upon rechallenge with Ag (16). Clonal deletion alone cannot account for the protection from diabetes, in that increasing numbers of BDC2.5 transgenic CD4$^+$ T cells were detected in the spleen, pancreases, and pancreatic lymph nodes in all protected animals examined as late as day 62 posttransfer. Upon rechallenge to Ag in vitro, cells from p31 I-A$^\alpha$-treated animals were hypoproliferative and produced increased levels of the anti-inflammatory cytokine IL-10 and decreased levels of inflammatory cytokine IFN-γ compared with cells from control-treated animal. Intracellular cytokine staining of cells ex vivo supported that splenic and pancreatic lymph node CD4$^+$ T cells from p31 I-A$^\alpha$-dimer-treated mice were producing increased IL-4 and IL-10 in vivo. Most importantly, treatment of mice with anti-IL-10R Ab reversed the tolerogenic effects of the dimer therapy. Thus, p31-I-A$^\alpha$ dimer treatment promotes death of pathogenic cells while promoting the development of regulatory cells producing IL-10. This altered immune response results in down-modulation of the autoimmune response to the autoantigen. The regulatory cells are similar to type 1 regulatory T cells that have been shown to suppress the response of both naive and memory T cells and Th1-mediated pathologies through bystander suppression (32). A previous study demonstrating the tolerogenic effect of HA peptide-MHC class II dimers in a system in which mice express a transgenic TCR specific for HA and express HA in pancreatic islets also attributed protection from diabetes to the induction of IL-10-producing regulatory T cells (19). Our studies extend these studies to demonstrate that the soluble bivalent...
peptide-MHC can induce IL-10 production in disease-relevant spontaneously diabetogenic T cells and as importantly, previously activated T cell populations more like what would be encountered in the new onset autoimmune setting.

The development of peptide I-A\(^{b}\) dimers allowed studies to be performed in autoimmune prone NOD mice in a nontransgenic system. p31 I-A\(^{b}\) dimers were found to identify a small population of cells in wild-type NOD mice. Treatment of NOD mice with p31 I-A\(^{b}\) dimers resulted in the increased production of IL-10 from 1040-31-reactive cells, but did not result in decreased IFN-\(\gamma\) production or in the induction of anergy. Furthermore, in preliminary studies, the p31 I-A\(^{b}\) dimer therapy was unable to prevent or delay diabetes caused by diabetogenic spleen cells from NOD mice or to reverse diabetes in newly diabetic NOD mice. There are several potential reasons why p31 I-A\(^{b}\) dimers were ineffective in these settings. One is that p31 I-A\(^{b}\) dimers may be present at too low of a frequency to overcome the diabetogenicity of other islet-reactive cells present. Multiple Ags are thought to be targeted in type 1 diabetes, and various autoreactive T cells are likely to be present. Peptide 1040-31-reactive cells were determined to be present in spleens of diabetic NOD mice by proliferation, but were below the level of detection by flow cytometry unless first expanded in vitro. Another recent study using BDC2.5 mimotope I-A\(^{b}\) tetramers also reported the BDC2.5 mimotope-reactive cells in NOD spleens at less than 0.3% of CD4\(^{+}\) cells (33). Treatment with p31 I-A\(^{b}\) dimers did alter the response of endogenous 1040-31-reactive cells, resulting in an increased production of IL-10 upon in vitro challenge. However, the level may have been too low to cause bystander suppression of other islet-reactive T cells. In the future, the effect of combinations of multiple peptide-MHC class II reagents can be tested. In NOD mice, \(-50\%\) of T cells infiltrating the pancreatic islets react with insulin, and 97% of the insulin-reactive T cells respond to the insulin peptide B(9–23) (34). Another possibility why p31 I-A\(^{b}\) dimers were ineffective in inducing tolerance in NOD mice is that cross-reacting cells may respond more anti-CD3 like while retaining the ability to target Ag-specific T cells. Further studies in spontaneous autoantigen-induced models of autoimmunity will be important to evaluate fully the therapeutic potential of peptide-MHC multimers.

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References


