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Cutting Edge: Type 1 Diabetes Occurs despite Robust Anergy among Endogenous Insulin-Specific CD4 T Cells in NOD Mice

Kristen E. Pauken,*† Jonathan L. Linehan,*‡ Justin A. Spanier,*† Nathanael L. Sahli,*† Lokesh A. Kalekar,*‡ Bryce A. Binstadt,*‡ James J. Moon,*‡ Daniel L. Mueller,*† Marc K. Jenkins,*‡* and Brian T. Fife*†

Insulin-specific CD4+ T cells are required for type 1 diabetes. How these cells are regulated and how tolerance breaks down are poorly understood because of a lack of reagents. Therefore, we used an enrichment method and tetramer reagents to track insulin-specific CD4+ T cells in diabetes-susceptible NOD and resistant B6 mice expressing I-A^d. Insulin-specific cells were detected in both strains, but they only became activated, produced IFN-γ, and infiltrated the pancreas in NOD mice. Unexpectedly, the majority of Ag-experienced cells in NOD mice displayed an anergic phenotype, but this population decreased with age as tolerance was lost. B6 mice expressing I-A^d were protected because insulin-specific cells did not become effector or anergic T cells but remained naive. These data suggest that NOD mice promote tolerance through anergy induction, but a small proportion of autoreactive T cells escape anergy to provoke type 1 diabetes. The Journal of Immunology, 2013, 191: 4913–4917.

Insulin is an immunodominant Ag during type 1 diabetes (T1D) (1–4). In NOD mice, >90% of insulin-specific CD4+ T cells in the pancreas are specific for the insulin B chain (InsB) peptide 9–23 (InsB9–23) (3), and these cells are required for T1D (5). In addition, tolerogenic immunization with InsB9–23 peptide delays or prevents T1D (6, 7). Despite the well-established role of insulin-specific CD4+ T cells during T1D, little is known about how this immune response develops because these cells have been difficult to track. There has not been an in-depth analysis of this critical CD4+ T cell population to understand how peripheral tolerance fails and T1D develops.

MHC class II tetramers are powerful reagents to track Ag-specific CD4+ T cells. When coupled with magnetic enrichment, rare cells can be tracked with high precision (8, 9). However, a major challenge in generating MHC class II tetramers is determining the peptide-binding register. The relevant binding register for the InsB10–23 epitope is debated (10–13). However, there is evidence that the majority of InsB10–23-reactive CD4+ T cells recognize the 14–22 core segment ALYLVCGER (register 3) when mutated to optimize binding to I-A^d (11, 12). Therefore, we constructed a tetramer reagent containing the modified register 3 epitope bound to I-A^d to define the dynamics of the insulin-specific CD4+ T cell response in diabetes-susceptible NOD mice, as well as resistant B6 mice expressing the I-A^d allele (B6.g7) (14). Our results led to the surprising conclusion that most InsB10–23r3:I-A^d-specific T cells are anergic in NOD mice but are naive in B6.g7 mice.

Materials and Methods

Mice

NOD mice were purchased from Taconic. B6.g7 mice were generated by Zucchi et al. (14). NOD.BDC2.5 mice were purchased from The Jackson Laboratory. NOD.BDC2.5 cells were isolated, as described (15), and 7500 naive T cells were transferred i.v. to 7–12-wk-old prediabetic NOD mice. Blood glucose ≥ 250 mg/dl indicated diabetes (LifeScan). All animal experiments were approved by the Institutional Animal Care and Use Committee of the University of Minnesota.

Insulin tetramer

The InsB10–23r3:I-A^d tetramer was constructed similarly as described (8). Briefly, I-A^d monomer containing the peptide HLVERLYLVCGEEG was produced and biotinylated in Drosophila S2 cells. Biotinylated monomer was purified on a monomeric avidin column (Thermo Scientific) and combined with streptavidin (SA)-PE and SA-allophycocyanin (Prozyme) to produce the tetramers. The National Institutes of Health tetramer core provided I-A^d hen egg lysozyme (HEL)11–25 tetramer (AMKRHGLDNYRGYSL).

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The online version of this article contains supplemental material.

Abbreviations used in this article: B6.g7, B6 mice expressing the I-A^d allele; HEL, hen egg lysozyme; InsB, insulin B chain; non-DLN, non-draining lymph node; pLN, pancreatic lymph node; SA, streptavidin; SLO, secondary lymphoid organ; T1D, type 1 diabetes; Treg, regulatory T cell.

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Flow cytometry

Single-cell suspensions were generated, as described (15). Tetramer-binding cells were enriched from the spleen and nondraining lymph nodes (non-dLNs; periaortica, inguinal, brachial, cervical, axillary, and mesenteric lymph nodes) by incubation with 10 nM PE- or allophycocyanin-tetramer for 1 h at 25°C, followed by anti-PE and anti-allophycocyanin MicroBeads for 30 min at 4°C and prior to elution on magnetic columns (Miltenyi Biotec).

Samples were collected using a BD LSR II and Fortessa (BD Biosciences). Data were analyzed using FlowJo software (TreeStar). Cells were enumerated using AccuCheck Counting Beads (Life Technologies).

Cytokine stimulation and priming

Cytokines from insulin-specific CD4+ T cells were assessed in vitro in complete DMEM containing 100 ng/ml PMA, 1000 ng/ml ionomycin, and 10 μg/ml brefeldin A (Sigma) for 4 h (15). For BDC2.5 T cells, 500 ng acetylated p31 peptide (NYRPLWVRME) (Genemed Synthesis) was injected i.v. for 4 h. The modified InsB10–23 peptide (11) or HEL11–25 (Genemed Synthesis) was emulsified in CFA. Mice were immunized s.c. in the flank.

Statistics

Unpaired two-tailed Student t tests were performed with a 95% confidence interval using GraphPad Prism 5 software.

Results and Discussion

Development of the InsB10–23r3:I-A^b tetramer reagent

We produced an I-A^b tetramer containing a variant of InsB10–23 with substitutions (InsB 10–23r3) to anchor the peptide in register 3, because previous work showed that this tetramer detects the majority of CD4+ T cells specific for the native peptide (11). Cells from NOD mice were enriched with InsB10–23r3:I-A^b or HEL11–25:I-A^b tetramers (control), as described (8). Small, but mutually exclusive, populations of tetramer-binding cells were detected among preimmune CD4+ T cells (Fig. 1A). As control, mice were primed with InsB10–23r3 and HEL11–25, and mutually exclusive tetramer populations expanded (Fig. 1A). Insulin-specific cells became activated, expressed CD44 (Fig. 1B, Supplemental Fig. 1C), and expanded (Fig. 1C).

A small degree of nonspecific binding of the InsB10–23r3:I-A^b tetramer was detected on CD8+ T cells (Supplemental Fig. 1A). To increase sensitivity, we stained cells from NOD mice simultaneously with InsB10–23r3:I-A^b/SA-PE and SA-alllophycocyanin tetrarmers (Supplemental Fig. 1A). All double tetramer-binding cells expressed CD4 but not CD8. This approach was used for the remainder of the study to eliminate background.

Insulin-specific CD4+ T cells only infiltrate the NOD pancreas

We next evaluated the dynamics of the InsB10–23r3:I-A^b–specific CD4+ T cells in diabetes-susceptible NOD and resistant B6.g7 mice. Insulin-specific CD4+ T cells were detected in the pancreatic lymph nodes (pLNs), spleen, and non-dLNs of both strains, consistent with work examining BDC2.5 mimotope-specific CD4+ T cells (Fig. 2A, 2B, Supplemental Fig. 1B) (16). The number of insulin-specific CD4+ T cells increased in the secondary lymphoid organs (SLOs) of NOD mice with age, peaking at 14 wk (Fig. 2A, Supplemental Table IA). There were significantly more insulin-reactive cells in the SLOs of NOD mice at all ages examined compared with B6.g7 mice (Fig. 2A, Supplemental Table IA). In B6.g7 mice, there was a slight, but not significant, increase in cell number between weeks 3 and 5 of life (Fig. 2A). The number of insulin-specific CD4+ T cells did not change in B6.g7 mice between weeks 5 and 20 (Fig. 2A, Supplemental Table IA). Importantly, insulin-specific CD4+ T cells infiltrated the pancreas of NOD mice but not B6.g7 mice (Fig. 2B, Supplemental Fig. 1B). These data demonstrate that insulin-specific CD4+ T cells escape central deletion in both NOD and B6.g7 mice but only infiltrate the pancreas in NOD mice.

We next examined the activation of insulin-specific CD4+ T cells by measuring CD44 expression. Work using BDC2.5 mice showed that activation can be impaired in diabetes-resistant hosts (17). We determined that there was a higher frequency (Fig. 2C, 2D) and number (Supplemental Table IB) of CD44^+ insulin-specific CD4+ T cells in NOD mice than in B6.g7 mice. The frequency of CD44^+ cells in the pLNs of NOD mice peaked between weeks 3 and 5, resulting in significantly more activated insulin-specific CD4+ T cells in NOD mice than in B6.g7 mice (Fig. 2D). These results suggest that InsB10–23r3:I-A^b–specific T cells become activated in the pLNs of NOD mice but not B6.g7 mice.

Insulin-specific CD4+ T cells differentiate into IFN-γ–producing Th1 cells in NOD mice

In NOD mice we observed a subpopulation of insulin-specific CD4+ T cells that became activated and infiltrated the pancreas. We speculated that these activated cells would produce IFN-γ, because this cytokine is involved in T1D pathogenesis (18, 19). Conversely, we predicted that IFN-γ would not be produced by insulin-specific CD4+ T cells in B6.g7 mice because these cells were a naive phenotype (Fig. 2C, 2D). We also examined TNF-α and IL-17A because of their predicted roles for T1D pathogenesis (20, 21). IFN-γ, TNF-α, and IL-17A were all detected in the polyclonal CD4+CD44^hi population in both NOD and B6.g7 mice (Supplemental Fig. 1F). Tetramer-binding cells in NOD mice produced IFN-γ and TNF-α but not IL-17A, whereas B6.g7 mice produced little to no IFN-γ or IL-17A (Fig. 3A). IFN-γ was enriched in CD44^hi cells in NOD mice (Supplemental Fig. 1D). TNF-α production by insulin-specific CD4+ T cells was detected in both strains, suggesting that the cells were viable (Fig. 3A) (22). These data support a model in which insulin-specific CD4+
T cells encounter Ag and differentiate into pathogenic Th1 cells in NOD mice, whereas failure to encounter autoantigen in B6.g7 mice leads to a lack of Th1 differentiation. Insulin-specific CD4+ T cells can differentiate into Foxp3+ regulatory T cells previous reports demonstrated that regulatory T cells (Tregs) influence the development of T1D (20). We examined the possibility that NOD mice had a decreased frequency of insulin-specific Tregs. However, Foxp3+ Tregs developed in both strains, and we did not measure a significant difference between NOD and B6.g7 mice (Fig. 3B). Therefore, we speculate that Ag-specific Tregs alone are not the main mechanism for diabetes resistance in the B6.g7 mouse. In fact, it appears that there are more Tregs in NOD mice compared with B6.g7 mice; however, this difference is not statistically significant.

T cell anergy develops in the pLNs of NOD mice It is thought that T1D develops as the result of the loss of peripheral tolerance. However, tolerance induction in the endogenous insulin-specific CD4+ T cell population has never been tested. We predicted that the majority of insulin-reactive T cells would escape tolerance and cause diabetes. However, we found that only a small subset of insulin-reactive T cells produced IFN-γ and infiltrated the pancreas (Figs. 2, 3). We speculated that Ag-experienced insulin-specific T cells might become anergized and be retained in the SLOs. To address this possibility, we took advantage of FR4 and CD73, which were recently identified as markers of T cell anergy on CD4+CD44highFoxp3- cells (23). Recent experiments that we performed in healthy hosts also identified FR4+CD73+ anergic cells within polyclonal CD4+ T cells (L.A. Kalekar, K.E. Pauken, J.L. Linehan, B.T. Fife, M.K. Jenkins, and D.L. Mueller, unpublished observations). To test this in T1D, we used our recently characterized adoptive-transfer model to study islet-specific CD4+ T cells (15). In this model, a low number of naive T cells from the BDC2.5 mouse were transferred into prediabetic NOD mice to mimic the endogenous population (15). By 3 wk posttransfer, the BDC2.5 CD4+ T cells developed an anergic phenotype (Foxp3- FR4+CD73+) (Fig. 4A, 4B). Surprisingly, more BDC2.5 CD4+ T cells in the pLNs were anergic (Fig. 4A, 4B) than were effector phenotype cells (FR4- CD73- CD44hiFoxp3-). In contrast, anergic phenotype cells were largely absent from the spleen and pancreas (Fig. 4A, 4B). To validate that coexpression of FR4 and CD73 correlated with functional anergy in diabeticogenic
T cells, we assessed IFN-γ in the pLNs. Following peptide challenge, IFN-γ was not produced by CD73\(^+\)FR4\(^+\)insulin-specific CD4\(^+\) T cells in the spleen and non-dLNs. Data are compiled from six experiments. Cells are gated on singlet\(^+\), CD3\(^+\), B220\(^-\), CD11b\(^-\), CD11c\(^-\), and CD4\(^-\)Foxp3\(^-\) cells. Data in (E) also include Thy1.1\(^+\), CD44\(^{high}\) cells, and data in (F) also include InsB10–23r3:MHCII\(^+\) PE\(^-\) and allophycocyanin\(^-\) tetrarmers. *p = 0.01–0.05, **p = 0.001–0.01, ***p < 0.001. ns, Not significant.

In conclusion, we developed an MHC class II tetramer that allows tracking of InsB10–23r3-insulin-specific CD4\(^+\) T cells. Despite the presence of pathogenic CD4\(^+\) T cells in NOD mice, an anergic population emerged specifically in the pLNs. This population diminished over time and was absent from the pancreas. In B6.g7 mice, insulin-specific cells remained naive, suggesting an absence of Ag encounter. Studying how insulin-specific CD4\(^+\) T cells become activated in NOD mice, but not in B6.g7 mice, may provide new insight into how tolerance is breached during T1D. It would be interesting to determine whether other InsB9–23 registers have the same bias toward anergy induction or whether these cells are more pathogenic (12, 24). Understanding how peptide/MHC binding impacts the effector potential of diabetogenic CD4\(^+\) T cells may aid in our therapeutic efforts to restore tolerance in T1D patients.
Acknowledgments

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Disclosures

The authors have no financial conflicts of interest.

References


Flow cytometric staining of tetramer positive CD4⁺ T cells and intracellular cytokines.

(A) (Left) CD44 and InsB₁₀₂₃:Ⅰ-A²²⁻ staining from CD4⁺ (top) and CD8⁺ T cells (bottom) from the spleen and non-draining LNs of a non-diabetic NOD. (Right) Double tetramer staining with the InsB₁₀₂₃:Ⅰ-A²²⁻ tetramers in PE and allophycocyanin (APC). Data is representative of fifty-two mice from fifteen independent experiments. Cells were gated on singlet⁺, CD3⁺, B220⁻, CD11b⁻, CD11c⁻, and CD4⁺ or CD8⁺ cells.

(B) Flow cytometry plots from the spleen combined with non-draining LNs, pancreatic LN (pLN), or pancreas of non-diabetic NOD (20 week old non-diabetic mouse representative of 8 mice from five experiments) and B6.g7 (21 week old mouse representative of 8 mice from three experiments). Double tetramer staining with the InsB₁₀₂₃:Ⅰ-A²²⁻ tetramers in PE and APC. Cells were gated on singlet⁺, CD3⁺, B220⁻, CD11b⁻, CD11c⁻, and CD4⁺.

(C) Flow cytometry plots from the spleen combined with non-draining LNs and the pLN of a NOD mouse primed with whole insulin protein emulsified in CFA (25μg/mouse). (Top) Double tetramer staining with the InsB₁₀₂₃:Ⅰ-A²²⁻ tetramers in PE and APC. Cells were gated on singlet⁺, CD3⁺ B220⁻, CD11b⁻, CD11c⁻, and CD4⁺. (Bottom) CD44 and PD-1 expression on insulin-specific CD4⁺ T cells from the upper right quadrant of the top flow plot. Cells are gated on singlet⁺, CD3⁺, B220⁻, CD11b⁻, CD11c⁻, and CD4⁺ InsB₁₀₂₃:Ⅰ-A²²⁻ PE⁺ and APC⁺. Data are representative of 14 NOD and 14 B6.g7 mice (9-10 weeks old) from five independent experiments.

(D) Frequency of CD44⁺⁺ or CD44⁺⁻ insulin-specific CD4⁺ T cells from combined SLO (spleen+non-draining LN+pLN) producing IFNγ. Data are compiled from nine experiments with B6.g7 (n=12), non-diabetic NOD (n=28), and diabetic NOD (n=9). Cells were gated on singlet⁺, B220⁻, CD11b⁻, CD11c⁻, CD4⁺, CD8a⁺, InsB₁₀₂₃:Ⅰ-A²²⁻-PE⁺ and InsB₁₀₂₃:Ⅰ-A²²⁻-APC⁺ and either CD44⁺⁺ or CD44⁺⁻.

(E) Frequency of effector phenotype (FR4⁺CD73⁻ CD44⁺⁺Foxp3⁻) and anergic phenotype (FR4⁺CD73⁻ CD44⁺⁺Foxp3+) IFNγ-producing CD4⁺ T cells from the spleen of pre-diabetic NOD mice following 2-4 hours in vivo stimulation with 100 μg anti-CD3 intravenously (clone 145-2C11, Bio X Cell). Data are compiled from three independent experiments with a total n=15 mice.

(F) Flow cytometric plots of cytokine staining from insulin-specific CD4⁺ T cells (top) compared to polyclonal CD4⁺ CD44⁺⁺ cells (bottom). Cells were pooled from pLN, spleen, and non-draining LNs of non-diabetic NOD or B6.g7 mice. Data are representative of nine experiments with B6.g7 (n=12), non-diabetic NOD (n=28), and diabetic NOD (n=9). Cells were gated on singlet⁺, B220⁻, CD11b⁻, CD11c⁻, CD4⁺, CD8a⁺, CD44⁺⁺, InsB₁₀₂₃:Ⅰ-A²²⁻ PE⁺ and APC⁺ cells (Top row), or singlet⁺, B220⁻, CD11b⁻, CD11c⁻, CD4⁺, CD8a⁺. tetramer⁺, CD44⁺⁺ (bottom row).
Supplemental Table I. Quantification of insulin-specific CD4⁺ T cells in NOD and B6.g7 mice.

A. Total Tetramer positive cells

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<th></th>
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B. CD44^{high} Tetramer positive cells

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<td>20 wks</td>
<td>13 ± 4</td>
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(A) InsB₁₀-2₃r₃:1⁻⁻⁻⁸⁷ cells that bind both the PE and allophycocyanin (APC) tetramer (double positive) in the spleen and non-dLNs, pLN, and pancreas of NOD and B6.g7 mice. Cells are gated on singlet−, CD3⁺, B220⁻, CD11b⁻, CD11c⁻, CD4⁺, CD8a⁻, InsB₁₀-2₃r₃:1⁻⁻⁻⁸⁷ PE⁻ and InsB₁₀-2₃r₃:1⁻⁻⁻⁸⁷ APC⁻. Non-diabetic NOD data at 3 weeks (n=9), 5 weeks (n=13), 14 weeks (n=13), and 20 weeks (n=17). Diabetic NOD data is from six mice. Data from B6.g7 mice at 3 weeks (n=4), 5 weeks (n=7), and 20 weeks (n=8). (B) Cells from (A) are gated on CD44^{high}.