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The Presence and Preferential Activation of Regulatory T Cells Diminish Adoptive Transfer of Autoimmune Diabetes by Polyclonal Nonobese Diabetic (NOD) T Cell Effectors into NSG versus NOD-scid Mice

Maximiliano Presa,* Yi-Guang Chen,† Alexandra E. Grier,* Edward H. Leiter,* Michael A. Brehm,‡ Dale L. Greiner,‡ Leonard D. Shultz,* and David V. Serreze*

NOD-scid.II2rg null (NSG) mice are currently being used as recipients to screen for pathogenic autoreactive T cells in type 1 diabetes (T1D) patients. We questioned whether the restriction of IL-2R γ-chain (II-2γ)-dependent cytokine signaling only to donor cells in NSG recipients differently influenced the activities of transferred diabetogenic T cells when they were introduced as a monoclonal/oligoclonal population versus being part of a polyclonal repertoire. Unexpectedly, a significantly decreased TID transfer by splenocytes from prediabetic NOD donors was observed in II-2γnull-NSG versus II-2γ–intact standard NOD-scid recipients. In contrast, NOD-derived monoclonal/oligoclonal TCR transgenic β cell–autoreactive T cells in either the CD8 (A14, NY8.3) or CD4 (BDC2.5) compartments transferred disease significantly more rapidly to NSG than to NOD-scid recipients. The reduced diabetes transfer efficiency by polyclonal T cells in NSG recipients was associated with enhanced activation of regulatory T cells (Tregs) mediated by NSG myeloid APC. This enhanced suppressor activity was associated with higher levels of Treg GITR expression in the presence of NSG than NOD-scid APC. These collective results indicate NSG recipients might be efficiently employed to test the activity of T1D patient–derived β cell–autoreactive T cell clones and lines, but, when screening for pathogenic effectors within polyclonal populations, Tregs should be removed from the transfer inoculum to avoid false-negative results. The Journal of Immunology, 2015, 195: 3011–3019.

Type 1 diabetes (T1D) in both humans and NOD mice results from the autoimmune destruction of insulin-producing pancreatic β cells mediated by the combined activity of pathogenic CD4 and CD8 T cells (1, 2). Although NOD mice develop TID through mechanisms that appear to be pathologically similar to the case in humans, this model is not perfect, as some disease interventions effective in these animals have not yet proven to be clinically translatable (3). These difficulties have prompted the development of multiple humanized mouse models that could potentially be used to assess human T cells for diabetogenic activity and to screen interventions that might attenuate such pathogenic effectors (4).

The most promising humanized mouse models are those derived from the immunodeficient NOD.Cg-Prkdcscid II2rg null (NSG) stock. This NOD congenic stock harbors the spontaneous scid mutation that eliminates mature T and B lymphocytes, and also an engineered null mutation in the II2rg gene (IL-2 common γ-chain receptor) that ablates signaling through the IL-2, IL-4, IL-7, IL-9, IL-15, and IL-21 cytokine receptors (4). These combined mutations, which prevent the development of functional NK cells as well as lymphocytes, in conjunction with unique features of the NOD genetic background, enable NSG mice to support engraftment with human cells and tissues far more efficiently than other immunodeficient strains (4).

In both humans and NOD mice, the primary TID genetic risk factor is provided by various combinations of MHC (designated HLA in humans)-encoded class I and II molecules (2). For this reason, NSG mice have also been further modified to transgenically express various human TID-associated HLA class I and class II molecules (5). In recent years, there have been several studies testing whether such NSG-HLA transgenic mouse stocks can be used to assess human T cells for diabetogenic activity. Adoptive transfer of PBMCs containing a polyclonal array of T cells from a human T1D patient carrying the HLA-A2.1 class I variant was reported to induce a leukocytic infiltration of pancreatic islets (insulitis) in NSG-HLA-A2.1 transgenic recipients (6). However, the specificity of this inflammatory response was unclear. There have been two other reports that a T1D patient–derived CD8 T cell clone or CD4 T cell lines recognizing β cell autoantigens can induce both insulitis and specific β cell death when engrafted into appropriate HLA transgenic NSG recipients (7, 8). It should be noted that, to date, transferred polyclonal or monoclonal T cells from T1D patient donors have not yet induced overt hyperglycemia in NSG recipients. Hence, whereas introduction of the inactivated II2rg gene enables higher engraftment levels of human T cells in NSG mice compared with first-generation NOD-scid recipients, this mutation’s negative effects on cytokine receptor signaling in host APC may also limit the functional activation of potential diabetogenic effectors in the

*The Jackson Laboratory, Bar Harbor, ME 04609; †Department of Pediatrics, Medical College of Wisconsin, Milwaukee, WI 53226; and ‡Program in Molecular Medicine, University of Massachusetts Medical School, Worcester, MA 01655

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Address correspondence and reprint requests to Dr. David V. Serreze, The Jackson Laboratory, 600 Main Street, Bar Harbor, ME 04609. E-mail address: dave.serreze@jax.org

Abbreviations used in this article: DC, dendritic cell; eGFP, enhanced GFP; PLN, pancreatic lymph node; TID, type 1 diabetes; Treg, regulatory T cell.

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transfer inoculum. Furthermore, in NSG recipients, IL-2rγ-dependent cytokine signaling is limited to donor cells. Consequently, different outcomes might ensue if the transferred diabetogenic T cells were monocolonal or oligoclonal in nature versus being a relatively small part of a polyclonal repertoire within a PBMC inoculum also containing donor APC.

Because of the above possibilities, we assessed whether the well-known ability of total splenocytes or β cell–autoreactive T cell clones derived from standard NOD donors to transfer TID to NOD-scid recipients was recapitulated in NSG hosts.

Materials and Methods

Mouse strains

NOD/ShiLtDvS, NOD-scid [NOD-Env30→CB17-Pkdcd6 (Eh)] and NOD (NOD.Pkdcd6-scid I2DQ3 (Wt)/Sid) donors were maintained in our specific-pathogen-free research colony at The Jackson Laboratory, NOD (NOD.Cg-Pkdcd6-scid I2DQ3 (Mmu/1Jc/Gk) were purchased from Taconic (Germantown, NY). A NOD stock transgenically expressing the TCR from the diabetogenic AH4 CD8 T cell clone, and also homozygous for an inactivated Rag1 allele (NOD.Rag1<sup>−/−</sup>A14HbTg(DvS)), and in this work designated NOD-bahs, has been previously described (9). NOD stocks transgenically expressing diabetogenic TCRs derived from the NY8.3 CD8<sup>+</sup> [NOD-Cg-Tg (TcrαTcrbNY8.3)1Pesa/DvsJ] (10) or BDC2.5 CD4<sup>+</sup> [NOD-Cg-Tg (TcrαBDC2.5,TcrbBDC2.5)1Doi/DvsJ] T cell clones (11) were acquired from the type 1 diabetes resource (http://type1diabetes.jax.org/) operated at The Jackson Laboratory. A N18 backcross generation NOD stock congenically carrying the previously described Foxp3<sup>−/−</sup>eGFP<sup>−/−</sup>Tcrb<sup>H2-Dkb1</sup>-Tcrb<sup>NY8.3</sup>b2g1 reporter construct (12) (formal designation NOD/LtDvS.J.Gt6-Foxp3<sup>−/−/−</sup>CD4<sup>−/−</sup>eGFP<sup>−/−</sup>TcrbDvSb2g1) was generated from the Foxp3<sup>−/−</sup>eGFP<sup>−/−</sup>Tcrb<sup>H2-Dkb1</sup>-Tcrb<sup>NY8.3</sup>b2g1 stock (25097) and in this work noted as NOD-Foxp3<sup>−/−</sup>eGFP<sup>−/−</sup> (JAX stock 25097) was generated and also typed as homozygous for NOD alleles at markers delineating all known Idd genetic loci (2). The enhanced GFP (eGFP) reporter is a knockin downstream of the Foxp3<sup>+</sup> promoter and coding sequences designed to ensure independent and functional expression of both proteins (12).

Abs and flow cytometry analyses

Various fluorochrome-labeled Abs specific for CD8 (53-6.72), CD4 (RM4-5), CD3 (145-2C11), TCRVα8.1 (B21-14), TCRVβ8.1.2 (KJ16), TCRVγ4 (KT4), CD44 (IM7.81), CD62L (MEL-14), CD25 (7D4), CD19 (ID3), CD11c (N418), CD62L (MEL-14), CD25 (7D4), CD19 (ID3), CD11c (N418), CD11b (M1/70), PDCA-1 (927), CD80 (16-10A1), CD86 (KT4), CD44 (IM7.81), CD62L (MEL-14), CD25 (7D4), CD19 (ID3), CD11c (N418), CD11b (M1/70), PDCA-1 (927), CD80 (16-10A1), CD86 (KT4), CLTA-4 (IB8), GITR (YGITR765), GITRL (YGL386), and CD70 (GL-1) were obtained from R&D Systems, BD Biosciences, or BioLegend (San Diego, CA). Anti-mouse CD25 (PC61.5) and CD4 (GK1.5) were purchased from BioLegend (San Diego, CA).

Statistical analysis

Data were analyzed using Prism software (GraphPad, San Diego, CA). For diabetes incidence, significance was calculated using log-rank (Mantel–Cox) test.

Results

Differential T1D induction in NSG recipients by polyclonal versus monocolonal autoreactive T cells

We compared the ability of total splenocytes from 6- to 8-wk-old NOD female donors to adoptively transfer TID to NOD-scid and NSG recipients. As expected, NOD splenocytes efficiently transferred TID to NOD-scid mice, but curiously induced a significantly lower level of disease in NSG recipients (Fig. 1A). In contrast, NOD-derived monocolonal CD8 T cells transgenically expressing the diabetogenic AH4 TCR (15) transferred disease significantly more rapidly to NSG than NOD-scid recipients (Fig. 1B). Thus, normally diabetogenic T cells residing within a polyclonal repertoire had a limited ability to transfer disease to NSG recipients, but a monocolonal population of such effectors efficiently did so.

Flow cytometric analyses of PBL from both recipient types of total NOD splenocytes showed a progressive increase in CD8 T cells posttransfer, but with significantly higher proportions in NSG than NOD-scid mice (Fig. 1C). The proportion of CD4 T cells increased over time to significantly higher levels in NOD-scid than NSG recipients (Fig. 1D). These data indicated the lack of IL-2rγ expression in NSG host cells resulted in differential engraftment of donor polyclonal CD8 and CD4 T cells compared with NOD-scid recipients. However, these data also indicated that a gross engraftment deficiency of adoptively transferred NOD polyclonal T cells did not account for their suppressed induction of T1D in NSG recipients. Furthermore, both NOD and NOD-scid recipients of total NOD splenocytes exhibited equivalent levels of donor B lymphocyte engraftment (data not shown).

Flow cytometric analyses of PBL from recipients of monoclonal AH4 CD8 T cells showed a higher proportion of such effectors in NSG than NOD-scid mice (Fig. 1E). As expected, PBL from either NOD-scid or NSG recipients of monoclonal AH4 cells did not contain CD4 T cells (Fig. 1F). Similar to the case for PBL, at 2 wk postransfer significantly higher numbers of transferred monoclonal AH4 CD8 T cells were detected in the spleens of NSG than NOD-scid recipients (Fig. 1G). In addition, analyses of activation markers on the same samples showed the proportion of effector-memory type...
a model of a common γ-chain cytokine. This assay (Fig. 2A) clearly showed an impaired ability of NSG-derived splenocytes to respond to the IL-2 common γ-chain cytokine. Based on this finding, we next tested whether the NSG environment allows some cell population present in standard NOD, but not NOD-AI4 donor splenocytes, to

**FIGURE 1.** T1D transfer to NOD-scid and NSG recipients by polyclonal versus monoclonal autoreactive T cells. (A) Adoptive transfer of T1D by total NOD splenocytes (5 × 10⁶) from prediabetic 6- to 8-wk-old female donors to NOD-scid (n = 20) and NSG (n = 20) recipients. (B) Adoptive transfer of T1D by monoclonal AI4 CD8 T cells (2.5 × 10⁶ NOD-AI4 splenocytes) to NOD-scid (n = 27) and NSG (n = 31) mice. In both (A) and (B), T1D development rates compared by log-rank (Mantel–Cox) test (***p < 0.0001). (C and D) Frequency over time following engraftment with total NOD splenocytes of CD8 and CD4 T cells among PBL in NOD-scid and NSG recipients. (E and F) Frequency over time following engraftment with NOD-AI4 splenocytes of CD8 and CD4 T cells among PBL in NOD-scid and NSG recipients. (G) Total AI4 T cell numbers (CD8⁺TCRVα8.3⁺) in secondary lymphoid tissues: spleen (SPL), PLN, and mesenteric lymph nodes (MLN). (H) Proportion of AI4 CD8 T cells with effector memory phenotype (CD44highCD62Llow). (G and H) Data from three independent experiments with a total n = 9 in each strain. In (C)–(H), *p < 0.05, **p < 0.001, ***p < 0.0001; ns, p > 0.05, two-way ANOVA with Bonferroni posttest correction.

**FIGURE 2.** The inability of NSG recipients to respond to common γ-chain cytokines is associated with an ability of NOD donor polyclonal T cells to impair T1D transfer by AI4 CD8 T cells. (A) Total splenocytes from NOD-scid or NSG mice (2.5 × 10⁵) were cultured in vitro in the presence of 10 pg/ml IL-2 and with or without 0.1% NaN₃ acting as inhibitor of cytokine translocation. After 3 d in culture, the amount of IL-2 remaining in the supernatant was quantified by ELISA. (B) NSG and NOD-scid mice were injected i.v. with a mixture of 2.5 × 10⁶ NOD-AI4 and 5 × 10⁶ standard NOD splenocytes. Data indicate T1D incidence from two independent experiments, total n = 20, for each strain. Disease incidence compared by log-rank (Mantel–Cox) test (***p < 0.0001). (C and D) At 2 wk posttransfer, the total number and activation phenotype of AI4 CD8⁺T cells in each type of recipient (n = 3 and 4, respectively, for NOD-scid and NSG recipients) were analyzed by flow cytometry in spleen (SPL), PLN, and mesenteric lymph node (MLN). In (A), (C), and (D), bars represent mean ± SEM. *p < 0.05, ***p < 0.0001; ns, p > 0.05; two-way ANOVA with Bonferroni posttest correction.

**Diabetogenic activity of monoclonal CD8 T cells in NSG recipients is suppressed in the presence of polyclonal NOD splenocytes**

The inactivated Il2rg gene in NSG host cells apparently contributes to the heightened ability of monoclonal AI4 CD8 T cells to engraft and induce T1D in this strain compared with NOD-scid recipients. Conversely, in contrast to standard NOD-scid recipients, polyclonal splenic NOD T cells could not efficiently induce T1D in NSG mice. We hypothesized these results could be explained by IL-2γ-dependent cytokine-signaling events only taking place in donor-derived cells in NSG recipients. To initially test this possibility, we compared the in vitro ability of residual myeloid splenocytes from NSG or NOD-scid mice to capture and internalize IL-2 as (CD44highCD62Llow) AI4 CD8 T cells in pancreatic lymph node (PLN) and mesenteric lymph nodes was significantly higher in NSG than NOD-scid recipients (Fig. 1H). This greater expansion and conversion to an effector memory phenotype of transferred monoclonal AI4 T cells in NSG than NOD-scid mice most likely account for why these effectors induced T1D more aggressively in the former recipients.

The activity of monoclonal CD8 T cells in NSG recipients is suppressed in the presence of polyclonal NOD splenocytes

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exert enhanced T1D-protective effects not elicited in NOD-scid recipients. This was done by determining whether the ability of monoclonal A14 T cells to aggressively mediate T1D development in NSG recipients was attenuated by cotransfer of NOD splenocytes. This was indeed the case (Fig. 2B). We next evaluated whether the presence of some NOD splenocyte-derived cell population(s) blocked engraftment of diabetogenic A14 CD8 T cells in NSG recipients. When cotransferred with NOD splenocytes, A14 T cells continued to engraft at significantly higher levels in the spleens of NSG than NOD-scid recipients (Fig. 2C). However, in contrast to when they were transferred alone, following coinfusion with NOD splenocytes, A14 T cells underwent significantly lower conversion levels to an effector memory phenotype in the PLNs of NSG than NOD-scid recipients (Fig. 2D). These collective findings indicate that when in a NSG, but not NOD-scid recipient environment, a NOD leukocyte population(s) acquires an enhanced ability to limit the cytopathic activation of diabetogenic T cells.

IL-2γr-dependent receptors that can bind, but not induce, cytokine signaling in host cells alter the engraftment of diabetogenic T cells without blocking their activation

The results described above indicated that when transferred alone into NSG, but not in NOD-scid recipients, common γ-chain cytokines produced by donor monoclonal A14 T cells would only be able to feed back to these pathogenic effectors. We reasoned such lessened receptor-mediated competition for IL-2γr-dependent cytokines in NSG than NOD-scid recipients could explain why, when engrafted alone, monoclonal A14 CD8 T cells elicit a more aggressive T1D onset in the former host environment. To further test this possibility, we analyzed another NOD-scid–related strain, NOG mice encoding an alternatively mutated version of the IL-2γr subunit that is expressed on the cell surface, but lacking a cytoplasmic domain needed to initiate cytokine signaling (5, 16). As a result, leukocytes in NOG mice can bind, but not respond, to IL-2γr-dependent cytokines. Thus, we tested whether a possible ability of host cells to limit availability of IL-2γr–dependent cytokines to pathogenic effectors resulted in less aggressive T1D development in NOG than NSG recipients of only monoclonal A14 CD8 T cells. Splenic engraftment levels of adoptively transferred monoclonal A14 T cells were significantly less in NOG than NSG recipients, but higher than in NOD-scid mice (Fig. 3A). This result might suggest that NSG-based stocks are a better choice if needed as recipients to exert enhanced T1D-protective effects not elicited in NOD-scid recipients. This was based on previous findings that the survival and immunosuppressive activity of the CD4+Foxp3+ subset of Tregs are highly IL-2 dependent (17). The A14 CD8 T cell clonotype does not require interactions with CD4 helper populations to efficiently induce T1D (15). Thus, we determined whether the capacity of total NOD splenocytes to inhibit the diabetogenic activity of cotransferred A14 CD8 T cells in NSG recipients required CD4 T cells. Flow cytometric analyses of PBL indicated only cotransfer of total and not CD4 T cell–depleted NOD splenocytes suppressed the engraftment levels of A14 T cells in NSG recipients (Fig. 4). Furthermore, total, but not CD4 T cell–depleted NOD splenocytes inhibited the ability of A14 T cells to transfer T1D to NSG recipients (Fig. 5A). These results demonstrated a CD4-expressing population(s) is responsible for the ability of total NOD splenocytes to inhibit disease induced by monoclonal A14 CD8 T cells in NSG recipients.

Polyclonal repertoire-derived CD4+Foxp3+ Tregs inhibit diabetogenic T cells in NSG recipients

Foxp3+ Tregs are a crucial CD4–coexpressing immunological suppressor subset (17). We used a newly developed NOD mouse stock in which an eGFP reporter is specifically expressed in Tregs (NOD.Foxp3+eGFP) to determine whether this immunosuppressive population differentially engrafts NOD-scid and NSG recipients. The NOD.Foxp3+eGFP stock develops T1D at a rate similar to standard NOD/LtDvs mice and expression of Foxp3 correlated with that of eGFP (Fig. 5B, 5C). Flow cytometric analyses of CD4+Foxp3+ Treg levels at different time points postengraftment with NOD.Foxp3+eGFP splenocytes showed no numerical strain differences between NOD-scid and NSG recipients (data not shown). This indicated the lower level of T1D development in NSG versus NOD-scid recipients of polyclonal NOD T cells is not due to a greater numerical engraftment of Tregs in the former strain. However, we hypothesized that enhanced Treg function may contribute to the limited

**FIGURE 3.** IL-2γr–dependent receptors that can bind, but not induce cytokine signaling in host cells alter the engraftment of diabetogenic T cells without blocking their activation. (A) At 2 wk posttransfer, three mice of each recipient type were euthanized, and spleen (SPL), PLN, and mesenteric lymph nodes (MLN) were analyzed for total A14 CD8+ T cell numbers by flow cytometry. Bars represent mean ± SEM; statistical analyses by two-way ANOVA with Bonferroni posttest correction. ns, p > 0.05; *p < 0.05, **p < 0.001. (B) Ten mice of each recipient type were assessed for T1D incidence. Log-rank (Mantel–Cox) test (***p < 0.0001).
To avoid the generation of newly differentiated Foxp3+ Tregs (Fig. 5D), NSG mice engrafted with reporter cell–depleted NOD.Foxp3-eGFP splenocytes were treated with a CD25-specific Ab to maintain Treg ablation. Total, but not Treg-depleted splenocytes from NOD.Foxp3-eGFP donors blocked T1D development in NSG recipients confused with A14 T cells (Fig. 5E). Furthermore, after being depleted of marked Tregs, NOD.Foxp3-eGFP splenocytes containing polyclonal T cell populations acquired an ability when transferred on their own to efficiently induce T1D in NSG recipients (Fig. 5F). Importantly, we also found the residual myeloid APC population in NSG mice supported Treg suppressive activity to a significantly greater extent than those of NOD-scid origin (Fig. 6A, 6B). In at least some circumstances, increased expression and activity of the GITR costimulatory molecule can enhance Treg function (18). Thus, we tested whether GITR expression by Tregs resident among NSG splenocytes differed when these cells were transferred alone or in combination with A14 effectors into NSG and NOD-scid recipients. Under both transfer situations, GITR expression by NOD donor splenocyte-derived Tregs, but not conventional T cells, was significantly higher in the PLNs of NSG than NOD-scid recipients (Fig. 6C, 6D). No differences were observed for GITR ligand expression (data not shown). Thus, the induction of a higher level of GITR expression may at least partially explain why Foxp3+ Tregs exert greater suppressive activity when interacting with myeloid APC in NSG than NOD-scid recipients.

FIGURE 4. CD4 T cells present in cotransferred NOD splenocytes inhibit the engraftment of diabeticogenic A14 CD8 T cell NSG recipient mice. NSG mice were injected i.v. with 2.5 × 10^6 NOD-A14 splenocytes alone or admixed with either total or CD4 T cell–depleted NOD splenocytes. Recipients of CD4-depleted splenocytes were injected i.p. with 200 μg depleting CD4-specific GK1.5 Ab once per week. The total number of CD4 T cell–depleted NOD splenocytes was adjusted to inject 2 × 10^6 CD8+ T cells, an equivalent amount to that in 5 × 10^6 total NOD splenocytes. Another control group received only CD4 T cell–depleted NOD splenocytes. At various time points posttransfer, PBL from each group of NSG recipients were analyzed by flow cytometry for numbers of A14 T cells (CD8+ TCRVα8.3+). Graph shows mean ± SEM. The statistics represent the significance of each group compared with controls receiving A14 T cells only. ns, p > 0.05; ***p < 0.001, two way ANOVA and Bonferroni posttest.

FIGURE 5. Polyclonal repertoire-derived CD4+Foxp3+ Tregs inhibit diabeticogenic T cells in NSG recipients. (A) Diabetes incidence in NSG mice injected i.v. with 2.5 × 10^6 monoclonal NOD-A14 splenocytes either alone or admixed with total or CD4 T cell–depleted NOD splenocytes. Mice receiving CD4 T cell–deficient splenocytes were injected i.p. with 200 μg depleting CD4–specific GK1.5 Ab once per week. The number of CD4-depleted NOD splenocytes was adjusted to inject 2 × 10^6 CD8+ T cells, an equivalent amount to that present in 5 × 10^6 total NOD splenocytes. Another control group received only CD4 T cell–depleted NOD splenocytes. At various time points posttransfer, PBL from each group of NSG recipients were analyzed by flow cytometry for numbers of A14 T cells (CD8+ TCRVα8.3+). Graph shows mean ± SEM. The statistics represent the significance of each group compared with controls receiving A14 T cells only. ns, p > 0.05; ***p < 0.001, two way ANOVA and Bonferroni posttest. (B) T1D incidence study comparing NOD.Foxp3-eGFP reporter mice with NOD/ShiLtDvs. Log-rank (Mantel–Cox) test, ns, p > 0.05. (C) Splenic cells from NOD.Foxp3-eGFP reporter mice were intracelularly stained with allophycocyanin (AP)-labeled anti-Foxp3 (FJK-16s) to test whether A14 T cells present in cotransferred NOD splenocytes inhibit the engraftment of diabetogenic AI4 CD8 T cell NSG recipient mice. NSG mice were infused with AI4 T cells alone or admixed with equal number of intact or reporter cell–depleted NOD. Foxp3-eGFP splenocytes. The number of intact or reporter cell–depleted NOD.Foxp3-eGFP splenocytes were adjusted to inject 2 × 10^6 total NOD splenocytes. Another group of each recipient type was kept without Ab treatment (dashed lines). At the indicated time point, PBL were analyzed by flow cytometry for proportions of eGFP reporter-expressing Tregs. Data represent the mean ± SEM (n = 5, each group). By 2 wk posttransfer, a significant increase in the proportion of CD4+Foxp3+ Tregs was observed in both types of recipients not receiving anti-CD25 Ab treatments. There were no significant differences between recipient strains in the anti-CD25–treated or untreated groups, ns, p > 0.05; ***p < 0.001, two-way ANOVA and Bonferroni posttest. (E) NSG mice were injected i.v. with 2.5 × 10^6 monoclonal NOD-A14 splenocytes either alone or admixed with total or reporter cell–depleted NOD.Foxp3-eGFP splenocytes. The number of intact or reporter cell–depleted NOD.Foxp3-eGFP splenocytes was adjusted to inject 2 × 10^6 CD8+ T cells. Mice receiving reporter cell–deficient NOD.Foxp3-eGFP splenocytes were also injected i.p. with 250 μg depleting CD25–specific PC61.5 Ab once per week to maintain Treg ablation. Mice receiving reporter cell–deficient NOD.Foxp3-eGFP splenocytes were also injected i.p. with 250 μg depleting CD25–specific PC61.5 Ab once per week to maintain Treg ablation. The incidence of T1D in various groups was compared by log-rank (Mantel–Cox) test, ***p < 0.0001.
The conventional CD4 and Treg populations were cocultured at the expression. The conventional CD4 T cells were then labeled with the eFlour 670 dye. The conventional CD4 T cells were then labeled with the eFlour 670 dye dilution) in the presence or absence of the indicated ratios of Foxp3+ Tregs and either NOD-scid or NSG APC. Numbers shown in each panel depict the mean percentage ± SEM of conventional CD4 T cells that remained in an undivided state (within the 0 dilution peak) under the indicated culture condition (n = 3 for each). (B) Summary of the percent suppression ± SEM (n = 3 for each culture condition) of conventional CD4 T cell responses in the presence versus the absence of Foxp3+ Tregs and either NOD-scid or NSG APC. Suppression was defined by the proportions of conventional CD4 T cells remaining in an undivided state. (Foxp3+ Treg-mediated suppression of conventional CD4 T cell proliferative responses significantly greater (p < 0.05, Student t test) in the presence of NSG than NOD-scid APC. (C) NSG or NOD-scid mice (n = 3 per group) were infused either with 5 × 10⁶ NOD-Foxp3-eGFP splenocytes alone or (D) in combination with 2.5 × 10⁶ NOD-AI4 splenocytes. At 10 d posttransfer, the mean fluorescence intensity (MFI) of GITR-specific Ab staining by residual myeloid APC from NSG mice support higher levels of Treg activity than those of NOD-scid origin. CD4 T cells within splenocytes from NOD-Foxp3-eGFP mice were sorted into conventional or Treg populations based on the respective absence or presence of eGFP marker expression. The conventional CD4 T cells were then labeled with the eFlour 670 dye. The conventional CD4 and Treg populations were cocultured at the indicated ratios for 2 d in the presence of 1 μg/ml anti-CD3 (1452C11) and 2 × 10⁵ NSG or NOD-scid splenic leukocytes as a source of APC. The percentages of proliferating conventional CD4 T cells were determined by flow cytometric analyses of eFlour 670 dilution. (A) Representative flow cytometric profiles of conventional CD4 T cell proliferation (indicated by eFlour 670 dye dilution) in the presence or absence of the indicated ratios of Foxp3+ Tregs and either NOD-scid or NSG APC. Numbers shown in each panel depict the mean percentage ± SEM of conventional CD4 T cells that remained in an undivided state (within the 0 dilution peak) under the indicated culture condition (n = 3 for each). (B) Summary of the percent suppression ± SEM (n = 3 for each culture condition) of conventional CD4 T cell responses in the presence versus the absence of Foxp3+ Tregs and either NOD-scid or NSG APC. Suppression was defined by the proportions of conventional CD4 T cells remaining in an undivided state.

We also evaluated whether the greater suppressor activity of Tregs detected in the presence of NSG than NOD-scid–derived myeloid APC could be related to a differing distribution of dendritic cell (DC) subsets in these two strains. Total numbers of splenic myeloid cells were significantly less in NSG than NOD-scid mice (Fig. 7A). After normalizing the data to 4 × 10⁶ total splenocytes (approximate mean level in NSG mice), analyses of the most common DC subsets and macrophages (19) by flow cytometry did not detect any significant proportional differences between the stocks (Fig. 7B).

Lower numbers of residual myeloid cells in NSG than NOD-scid mice do not correlate with proportional strain differences in common APC subsets. Collagenase D–digested splenocytes obtained from 7-wk-old NOD-scid and NSG mice were counted and stained with fluorochrome-conjugated Abs for flow cytometric analyses of common APC subsets. (A) Data represent the total number of myeloid residual spleen cell populations (mean ± SEM, n = 11 each strain). ***p < 0.0001, Student t test. (B) APC subsets from spleen of NOD-scid and NSG mice were analyzed by flow cytometry. Live single cells were gated on CD45.1+CD3+CD19− myeloid cells and were subset classified based on expression of the following markers: cDC CD8+, CD11b+CD11chiCD8α−; pDC CD4+, CD11b+CD11clowCD8α+; Tip DC, CD11b+CD11chiCD8α+; pDC, CD11b+CD11clowPDCA-1+; Mac, CD11b+CD11cint. Values are normalized to the ~4 × 10⁶ cells present in NSG spleens. Data represent mean ± SEM, n = 11 each strain. ns, p > 0.05; two-way ANOVA and Bonferroni posttest.

**FIGURE 6.** Residual myeloid APC from NSG mice support higher levels of Treg activity than those of NOD-scid origin. CD4 T cells within splenocytes from NOD-Foxp3-eGFP mice were sorted into conventional or Treg populations based on the respective absence or presence of eGFP marker expression. The conventional CD4 T cells were then labeled with the eFlour 670 dye. The conventional CD4 and Treg populations were cocultured at the indicated ratios for 2 d in the presence of 1 μg/ml anti-CD3 (1452C11) and 2 × 10⁵ NSG or NOD-scid splenic leukocytes as a source of APC. The percentages of proliferating conventional CD4 T cells were determined by flow cytometric analyses of eFlour 670 dilution. (A) Representative flow cytometric profiles of conventional CD4 T cell proliferation (indicated by eFlour 670 dye dilution) in the presence or absence of the indicated ratios of Foxp3+ Tregs and either NOD-scid or NSG APC. Numbers shown in each panel depict the mean percentage ± SEM of conventional CD4 T cells that remained in an undivided state (within the 0 dilution peak) under the indicated culture condition (n = 3 for each). (B) Summary of the percent suppression ± SEM (n = 3 for each culture condition) of conventional CD4 T cell responses in the presence versus the absence of Foxp3+ Tregs and either NOD-scid or NSG APC. Suppression was defined by the proportions of conventional CD4 T cells remaining in an undivided state.

**FIGURE 7.** Lower numbers of residual myeloid cells in NSG than NOD-scid mice do not correlate with proportional strain differences in common APC subsets. Collagenase D–digested splenocytes obtained from 7-wk-old NOD-scid and NSG mice were counted and stained with fluorochrome-conjugated Abs for flow cytometric analyses of common APC subsets. (A) Data represent the total number of myeloid residual spleen cell populations (mean ± SEM, n = 11 each strain). ***p < 0.0001, Student t test. (B) APC subsets from spleen of NOD-scid and NSG mice were analyzed by flow cytometry. Live single cells were gated on CD45.1+CD3+CD19− myeloid cells and were subset classified based on expression of the following markers: cDC CD8+, CD11b+CD11chiCD8α−; pDC CD4+, CD11b+CD11clowCD8α+; Tip DC, CD11b+CD11chiCD8α+; pDC, CD11b+CD11clowPDCA-1+; Mac, CD11b+CD11cint. Values are normalized to the ~4 × 10⁶ cells present in NSG spleens. Data represent mean ± SEM, n = 11 each strain. ns, p > 0.05; two-way ANOVA and Bonferroni posttest.

**Oligoclonal β cell–autoreactive MHC class I– and II–restricted T cells more readily induce T1D in NSG than NOD-scid recipients**

To analyze whether the accelerated T1D development in NSG mice mediated by adoptively transferred monocolonal A4 CD8 T cells was a phenomenon restricted to this clone, we tested the capacity of other NOD-derived MHC class I– and class II–restricted β cell–autoreactive TCR transgenic T cells to induce disease in such recipients. NOD-NY8.3 mice transgenically express the TCR of a potent diabetogenic CD8 T cell clone specific for a peptide derived from islet-specific glucose-6-phosphatase catalytic subunit-related protein (IGRP206–214) (20). Because the used NOD-NY8.3 stock does not also carry the scid or a rag gene knockout mutation, it produces NY8.3 CD8 T cells as an oligoclonal rather than a monocolonal population. Indeed, the residual CD4 T cells present in NOD-NY8.3 mice have been reported to enhance the diabetogenic activity of the NY8.3 effectors (10). Similar to the case with monocolonal A4 effectors, oligoclonal NY8.3 CD8 T cells transferred T1D...
significantly more rapidly to NSG than NOD-scid recipients (Fig. 8A). Analyses of PBL at 3 wk posttransfer in mice receiving NOD-NY8.3 splenocytes showed a greater proportion of total and tetramer-specific NY8.3 CD8+ T cells in NSG than NOD-scid recipients (Fig. 8B). Conversely, the proportion of NOD-8.3 donor-derived residual CD4+ T cells was higher in NOD-scid than NSG recipients (Fig. 8B). Although CD4+ Foxp3+ Tregs are phenotypically present in NOD-NY8.3 mice (~20% of total residual CD4+ T cells in spleen), their function is clearly not sufficient to suppress the diabetogenic activity of NY8.3 effectors in the donors. The residual phenotypic Tregs present in the NY8.3 donor cell inoculum engrafted at higher levels in NOD-scid than NSG recipients (Fig. 8C). The potential importance of this engraftment difference is questionable because we also found that, when depleted of Tregs, the NY8.3 donor cell inoculum continued to more readily induce T1D in NSG than NOD-scid recipients (data not shown). However, similar to the case for monoclonal AI4 cells, the higher engraftment levels of oligoclonal NY8.3 effectors in NSG than NOD-scid recipients are most likely an important factor for the more aggressive T1D development in the former host environment.

We also tested whether an oligoclonal population of diabetogenic CD4+ T cells differed in their capacity to transfer disease to NSG and NOD-scid recipients. Indeed, when transferred as an oligoclonal population, autoreactive BDC2.5 TCR transgenic CD4+ T cells induced T1D more efficiently in NSG than NOD-scid recipients (Fig. 8D). It should be noted that NOD-BDC2.5 mice producing such CD4 effectors as an oligoclonal population have a very low T1D incidence (21, 22). By contrast, when residual nontransgenic CD4+ T cells were analyzed by FACS at 3 wk posttransfer, for presence of donor-derived residual CD4+ T cells was higher in NOD-scid than NSG recipients (Fig. 8B). Conversely, the proportion of NOD-NY8.3 recipients IL-2rα-dependent cytokine-signaling events can only occur in donor-type cells, this may influence the activities of transferred diabetogenic T cells in ways that differ depending on whether such effectors were induced as a monoclonal population versus being part of an oligoclonal or polyclonal repertoire.

To initially test the above hypothesis, we determined whether the previously well-documented ability of total standard NOD splenocytes or a monoclonal TCR transgenic β-cells–autoreactive CD8 T cell clonotype (AI4) to transfer T1D to NOD-scid recipients was recapitulated in NSG hosts. As expected, adoptively transferred β-cell–autoreactive AI4 mononuclear CD8 T cells elicited T1D development in NOD-scid controls, but interestingly engrafted at higher levels and induced more aggressive disease onset in NSG recipients. Unlike NSG mice, the NOD-scid–modified NOG stock expresses receptors that can bind IL-2rα–dependent cytokines, but not in NSG mice. Total splenocytes from recently diabetic NOD-NY8.3 females were adjusted to inject i.v. 2.5 × 10^7 NY8.3 CD8 T cells into 8- to 10-wk-old NOD-scid or NSG females. (A) Diabetes incidence study showing representative results from three experiments. PBL from mice receiving NY8.3 T cells were analyzed by FACS at 3 wk posttransfer, for presence of (B) CD4+, CD8+, tetramer-specific NY8.3 CD8+ T cells and (C) for presence of CD4+Foxp3+ T cells. A total of 1.5 × 10^6 purified splenic CD4+ T cells from NOD-BDC2.5 mice was injected i.v. into NOD-scid or NSG mice. (D) Mice were monitored for diabetes development. (E) At 2 wk posttransfer, the proportion of circulating Foxp3+ Tregs was assessed by FACS in PBL isolated from mice receiving CD4+ T cells from NOD-BDC2.5 donors. (F) A total of 2 × 10^6 purified CD4+CD25− T cells from NOD-BDC2.5 donors was injected i.v. into NOD-scid (n = 10) or NSG (n = 10) mice; diabetes incidence is shown. Data represent mean ± SEM. **p < 0.001, ***p < 0.0001, ****p < 0.00001, nonparametric t test (Mann–Whitney).
does not enable them to induce signaling responses. Nonetheless, despite possible differences in host cell–mediated competition for binding of IL-2γ-dependent cytokines, T1D transfer kinetics by monoclonal AI4 T cells in NOD and NSG were comparable. Thus, diminished receptor-mediated competition by host cells for IL-2γ-dependent cytokines that we demonstrated would occur in NSG versus NOD-scid mice is unlikely to solely account for why adoptively transferred monoclonal AI4 CD8 T cells induce a more aggressive T1D onset in the former recipients.

Diametrically opposite results were obtained when NOD diabetogenic T cells were introduced into NOD-scid and NSG recipients as a broad polyclonal repertoire. In this case, polyclonal NOD splenocytes induced a significantly lower level of T1D in NSG than NOD-scid recipients. Interestingly, cotransfer of total NOD splenocytes inhibited the ability of monoclonal AI4 T cells to induce T1D in NSG recipients. This inhibitory activity was ultimately traced to enhanced activity, but not numbers, of CD4+Foxp3+ Tregs present in polyclonal NOD splenocytes upon transfer into NSG recipients. Indeed, when first depleted of Tregs, NOD splenocytes on their own efficiently transferred T1D to NSG recipients. The question then becomes why the functional activity of Tregs resident among NOD polyclonal T cells populations only reaches a T1D-protective level when transferred into NSG recipients. Again, the most likely explanation lies in the fact that, in NSG recipients, IL-2γ-dependent cytokine-signaling events only occur in donor cells. The survival and activities of Tregs are highly dependent on IL-2 (17). Thus, the lack of host cell–mediated receptor competition in NSG recipients, demonstrated in part by our current studies, may enhance IL-2 availability to Tregs resident among transferred NOD splenocytes and increase their functional activity to T1D inhibitory levels. This possibility is further supported by previous reports that IL-2 treatment inhibits T1D development in NOD mice by boosting Treg activity (26, 27). The lack of host cell–mediated receptor competition may also enable other IL-2γ-dependent cytokines to contribute to enhanced donor Treg activity in NSG recipients. Indeed, a recent study indicated that, at least under some circumstances, IL-15 contributes to the accumulation of Tregs (28). Furthermore, it has been reported that IL-21–dependent signaling events are required for the normal ability of NOD APC to exert diabetogenic activity (29). Regardless of the particular cytokine(s) involved, our current results indicate that NOD APC in which IL-2γ-dependent signaling responses do not occur may be preferentially skewed to a state promoting the maintenance of T1D-protective immune tolerance through an enhanced capacity to elicit Treg activity. Our studies did not find significant recipient strain differences in the proportions of common DC and macrophage subsets or their expression patterns of analyzed T cell costimulatory or inhibitory molecules that could account for the greater ability of NSG-derived APC to support Treg activity. However, we did find that GITR was expressed at significantly higher levels by NOD donor Tregs, but not conventional T cells, when interacting with myeloid APC in NSG than NOD-scid recipients. Previous studies (18) found at least under some conditions that increases in GITR expression and activity can enhance the suppressive activity of Tregs.

Our results utilizing the A14 system can be extended to other diabetogenic TCR transgenic models such as NOD-NY8.3 and NOD-BDC2.5. We are aware that our results indicating oligoclonal NY8.3 CD8 T cells efficiently transfer T1D to NSG mice contradict an earlier report that such donor cells poorly induce disease in the same recipients, which was attributed to a lack of IL-15 signaling in host APC (30). Although the true basis for this discrepancy remains unknown, it might be attributable to a varying dose of transferred NY8.3 splenocytes that was not detailed in this previous study, or differing environmental conditions. Regardless, our results indicate that in order for a range of diabetogenic T cells to induce disease in NSG recipients, they must either be introduced as monoclonal or oligoclonal populations or, if part of a polyclonal repertoire, the transfer inoculum must be first purged of Tregs. Another consideration is that, whereas NK cells remain present in NOD-scid mice, they are absent in the NSG strain (5). Hence, the augmented ability of monoclonal or oligoclonal diabetogenic T cells to induce disease onset in NSG recipients is a NK cell–independent process.

In conclusion, our findings reveal some important considerations that may be applicable when contemplating the possible use of NSG mice as recipients to screen for the presence of diabetogenic T cells resident within various human donor cell inocula, or as a resource to develop means to attenuate such effectors. Our results indicate that NSG-based models may be good recipients for studies entailing the transfer of β cell–autoimmune T cell clones or lines from human donors. Other results indicate that if the goal is to maximize expansion of a transferred clonal population of diabetogenic T cells in murine recipients, then NSG may be preferable to NOG mice for this purpose. Finally, the current results indicate that, when considering the use of NSG recipients to test for the presence of diabetogenic effectors among polyclonal or even some oligoclonal populations of human T cells, Tregs should first be removed from the transfer inoculum to eliminate false-negative results.

Disclosures

The authors have no financial conflicts of interest.

References


