Testing the Role of P2X7 Receptors in the Development of Type 1 Diabetes in Nonobese Diabetic Mice

Yi-Guang Chen, Felix Scheuplein, John P. Driver, Amanda A. Hewes, Peter C. Reifsnyder, Edward H. Leiter and David V. Serreze

*J Immunol* 2011; 186:4278-4284; Prepublished online 25 February 2011;
doi: 10.4049/jimmunol.1003733
http://www.jimmunol.org/content/186/7/4278

**References**
This article cites 34 articles, 26 of which you can access for free at:
http://www.jimmunol.org/content/186/7/4278.full#ref-list-1

**Subscription**
Information about subscribing to *The Journal of Immunology* is online at:
http://jimmunol.org/subscription

**Permissions**
Submit copyright permission requests at:
http://www.aai.org/About/Publications/JI/copyright.html

**Email Alerts**
Receive free email-alerts when new articles cite this article. Sign up at:
http://jimmunol.org/alerts
Testing the Role of P2X7 Receptors in the Development of Type 1 Diabetes in Nonobese Diabetic Mice

Yi-Guang Chen, Felix Scheuplein, John P. Driver, Amanda A. Hewes, Peter C. Reifsnnyder, Edward H. Leiter, and David V. Serreze

Although P2rx7 has been proposed as a type 1 diabetes (T1D) susceptibility gene in NOD mice, its potential pathogenic role has not been directly determined. To test this possibility, we generated a new NOD stock deficient in P2X7 receptors. T1D development was not altered by P2X7 ablation. Previous studies found CD38 knockout (KO) NOD mice developed accelerated T1D partly because of a loss of CD4+ invariant NKT (iNKT) cells and Foxp3+ regulatory T cells (Tregs). These immunoregulatory T cell populations are highly sensitive to NAD-induced cell death activated by ADP ribosyltransferase-2 (ART2)-mediated ADP ribosylation of P2X7 receptors. Therefore, we asked whether T1D acceleration was suppressed in a double-KO NOD stock lacking both P2X7 and CD38 by rescuing CD4+ iNKT cells and Tregs from NAD-induced cell death. We demonstrated that P2X7 was required for T1D acceleration induced by CD38 deficiency. The CD38 KO-induced defects in homeostasis of CD4+ iNKT cells and Tregs were corrected by coablation of P2X7. T1D acceleration in CD38-deficient NOD mice also requires ART2 expression. If increased ADP ribosylation of P2X7 in CD38-deficient NOD mice underlies disease acceleration, then a comparable T1D incidence should be induced by coablation of both CD38 and ART2, or CD38 and P2X7. However, a previously established NOD stock deficient in both CD38 and ART2 expression is T1D resistant. This study demonstrated the presence of a T1D resistance gene closely linked to the ablated Cd38 allele in the previously reported NOD stock also lacking ART2, but not in the newly generated CD38/P2X7 double-KO line. The Journal of Immunology, 2011, 186: 4278–4284.
sequent loss by NICD. CD4+ iNKT cells are extremely sensitive to NICD, most likely because of high expression levels of both ART2 and P2X7 (18, 21). Similarly, Tregs have also been reported to be highly sensitive to NICD (22).

The collective results described earlier suggested, but did not directly assess, whether T1D acceleration in NOD.CD38−/− mice also relies on the presence of P2X7 molecules. It was also unknown whether concurrent deficiency of P2X7 molecules could restore iNKT cells and Tregs in the CD38 KO stock to the levels observed in standard NOD mice. Furthermore, it remains to be determined whether independent of its role in mediating the loss of immunoregulatory populations through an NICD mechanism, P2X7 might also contribute to T1D development through its capacity to serve as an ATP sensor in macrophages and T cells that respectively promotes IL-1β secretion and effector function activation (23). To directly test these possibilities, we determined whether T1D development was altered in a newly generated P2X7−/− deficient NOD stock. We also determined whether a functional interaction between CD38 and P2X7 molecules modulates T1D development.

**Materials and Methods**

**Mice**

P2x7 KO mice on the C57BL/6J background were originally obtained from the Induced Mutant Resource at The Jackson Laboratory (JAX stock no. 5576) (24) and the mutation backcrossed to the NOD/LdDs strain. Linkage markers delineating all known Idd genetic loci have been fixed to homozygosity for NOD alleles in the strain now designated NOD.P2x7−/−. Currently maintained at the N9 backcross generation with a congenic interval of ∼49 Mb (the proximal boundary between D5Mit259 and P2x7; the distal boundary between D5Mit138 and D5Mit098). The donor strain congenic interval of the previously reported NOD.CD38−/− mouse stock has been further shortened (17) (Fig. 6A). The newly developed NOD.CD38−/− mouse stock was then used to generate NOD.CD38−/−/P2X7−/− mice. Because the CD38 and P2x7 genes are both on chromosome 5, this required identification and breeding of a double recombinant (17). NOD:ART2−/− mice have been previously described (17). A stock of NOD mice deficient in both CD38 and ART2 molecules was also generated with the newly developed NOD:CD38−/− strain, denoted as NOD:CD38−/−<short> ART2−/− hereafter. To distinguish the new NOD:CD38−/−<short> ART2−/− stock from the previously described NOD:CD38−/<short>ART2−/− stock with the longer congenic interval around the CD38 locus, we denoted the latter as NOD:CD38−/<long> ART2−/− hereafter.

**Flow cytometry**

RBC-depleted single-cell suspensions were prepared from spleens and pancreatic lymph nodes (PLNs). P2X7 expression by T cells was analyzed by staining leukocytes with the unconjugated HANO43 Ab and allo-phycocyanin-conjugated anti-CD3e (clone 145-2C11) followed by FITC-conjugated polyclonal goat anti-rat Ig. Tregs were identified by surface staining with anti-CD4 (clone RM4-5) and anti-CD25 (clone PC6), and intracellular staining with anti-Foxp3 (clone FJK-16s) according to instructions of the kit from eBioscience (San Diego, CA). For iNKT cell staining, cells were first treated with Fc block (anti-CD16/CD32, clone 2.4G2) at room temperature for 10 min and then incubated with a mixture containing anti-CD4, anti-TCRε, and the α-galactosylceramide (α-GalCer) analog PBS-57 loaded CD1d-tetramer (obtained from National Institutes of Health tetramer core facility) at 4˚C for 30 min. Stained cells were washed and analyzed on a FACSCalibur flow cytometer (Becton Dickinson) using CellQuest software. Anti-CD4, anti-CD3ε, anti-CD25, and anti-TCRε were purchased from BD Biosciences (San Jose, CA). Anti-P2X7 was obtained from Enzo Biosciences (Plymouth Meeting, PA). To analyze iNKT cell functional activity, we injected mice i.v. with 2 μg α-GalCer (Enzo Life Sciences). Production of IFN-γ and IL-4 by iNKT cells was analyzed by intracellular staining at 2 h after α-GalCer administration. Stained cells were analyzed on an LSRII flow cytometer (Becton Dickinson). Both IFN-γ and IL-4 Abs were from eBioscience.

**NICD analysis**

To determine the effect of NAD on T cell viability, RBC-depleted splenocytes (5 × 10^6/ml) were incubated in previously described RPMI 1640 tissue culture medium (25) containing varying concentrations of NAD (Sigma, St. Louis, MO) at 37˚C for 30 min. Cells were then washed and resuspended in Annexin V friendly FACS buffer, and stained with Annexin V (BD Biosciences) and anti-CD3ε at 4˚C for 30 min as described previously (18). Propidium iodine was added to all samples before analyses on a FACSCalibur flow cytometer (Becton Dickinson).

**T1D incidence study**

T1D was assessed by weekly monitoring of glycosuria development with Ames Diastrix (Diagnostics Division, Bayer, Elkhart, IN), and disease onset was defined as two consecutive values ≥3.

**In vitro Treg assay**

Treg assays were performed as previously described (26). In brief, splenic CD4 T cells were purified from 6–8-wk-old mice by depleting B220−, CD8−, and CD11b− cells with the previously described magnetic bead system. The CD25+ fraction was further isolated by staining with biotinylated anti-CD25 (clone 7D4) followed by streptavidin-conjugated microbeads (Miltenyi Biotec). CD4+CD25+ cells were then enriched by positive selection using an LS column (Miltenyi Biotec). The CD4+CD25− fraction was used as the effector population. Effector cells were labeled with CFSE as previously described. Labeled effector cells (5 × 10^5) were cocultured in triplicate with indicated numbers of CD4+CD25+ Tregs in the presence of 2 × 10^5 NOD.scid splenocytes and 5 μg/ml anti-CD3 (clone 145-2C11, BD Bioscience) in round-bottom 96-well tissue culture plates in a final volume of 200 μl of the previously described culture medium (25). Proliferation of effector cells was determined after 3 d of culture by CFSE dilution.

**Results**

Expression levels of P2X7 receptors dictate the sensitivity of mature T cells to NICD

We first confirmed the absence of P2X7 protein expression and function in NOD.P2X7−/− mice. P2X7 expression was assessed by flow cytometry and functional activity assayed by the sensitivity of mature T cells to NICD. As shown in Fig. 1A, expression of P2X7 on the surface of splenic T cells was completely absent in

![FIGURE 1.](http://www.jimmunol.org/Downloadedfrom/image)
P2X<sub>7</sub> deficiency alone does not alter T1D development in NOD mice

To determine whether P2X<sub>7</sub> plays a role in the development of T1D in NOD mice, disease onset rates were compared for littermates carrying the wild-type (+/+), heterozygous (+/−), or homozygous (−/−) P2x<sub>7</sub> KO alleles. In both male and female mice, no significant differences were found between any genotypes (Fig. 2).

CD38 deficiency-induced T1D acceleration in NOD mice is P2X<sub>7</sub> dependent

Our previous studies suggested, but did not definitively demonstrate, that CD38 deficiency-induced T1D acceleration in NOD mice needs an intact NICD pathway, that is, ART2-mediated ADP ribosylation of P2X<sub>7</sub> molecules (17). To directly test this hypothesis, we intercrossed CD38 and P2X<sub>7</sub>-deficient NOD stocks and generated NOD.CD38<sup>−/−</sup>/P2X<sub>7</sub>−/− double-KO (DKO) NOD mice. While P2X<sub>7</sub>−/− wild-type and CD38-deficient DKO mice exhibited greatly accelerated T1D development compared with standard NOD mice (Fig. 3), although P2X<sub>7</sub>−/− female mice were completely resistant to NICD (Fig. 1B), interestingly, P2X<sub>7</sub> expression levels were directly correlated with the proportions of T cells undergoing ADP ribosylation and activation of P2X<sub>7</sub> molecules (Fig. 2). During the preparation process (27), P2X<sub>7</sub> deficiency alone did not significantly affect disease onset (Fig. 2), its absence completely abrogated accelerated T1D development in CD38-deficient DKO mice (p = 0.2712, NOD versus NOD.CD38<sup>−/−</sup>/P2X<sub>7</sub>−/−; Fig. 3). Therefore, we conclude that ADP ribosylation of P2X<sub>7</sub> receptors and consequent triggering of NICD play an important role to promote accelerated T1D development in NOD.CD38<sup>−/−</sup> mice. We noted that the rate of T1D development is slightly greater in NOD.CD38<sup>−/−</sup>/P2X<sub>7</sub>−/− than in NOD.P2X<sub>7</sub>−/− mice. This suggests that in the absence of CD38 molecules, ART2 may promote T1D development independent of P2X<sub>7</sub> by ADP ribosylation of other proteins. This possibility will be the subject of future studies.

P2X<sub>7</sub> deficiency rescues the depleted iNKT and Treg compartments in NOD.CD38<sup>−/−</sup> mice

T1D acceleration in NOD.CD38<sup>−/−</sup> mice is associated with a loss of peripheral CD4<sup>+</sup> iNKT cells (18). Therefore, we asked whether
the frequencies and numbers of CD4+ iNKT cells in the NOD. CD38−/−.P2X7−/− stock are restored to the levels in standard NOD mice. We determined the numbers of CD4+ and double negative (DN) iNKT cells in the spleens and PLNs of standard NOD, NOD.CD38−/−, NOD.P2X7−/−, and NOD.CD38−/−.P2X7−/− mice. As expected, the NOD.CD38−/− stock had significantly reduced numbers of splenic CD4+ iNKT cells compared with standard NOD mice (Fig. 4A). Interestingly, numbers of splenic CD4+ iNKT cells were not only restored in the NOD.CD38−/− stock but actually greater than in standard NOD mice (Fig. 4A). This was also true for NOD.P2X7−/− mice (Fig. 4A). Therefore, the loss of immunoregulatory CD4+ iNKT cells in NOD.CD38−/− mice is a P2X7-dependent process. However, P2X7 ablation also allows for an expansion of CD4+ iNKT cells in CD38 intact NOD mice. Consistent with our previous results (18), standard NOD and NOD.CD38−/− mice had similar levels of splenic DN iNKT cells (Fig. 4B). Compared with standard NOD mice, the NOD.CD38−/−.P2X7−/− stock, but not NOD.P2X7−/− mice, also had increased numbers of splenic DN iNKT cells (Fig. 4B). Similarly, the loss of CD4+ iNKT cells in the PLNs of NOD.CD38−/− mice was also rescued by the concomitant deficiency of P2X7 molecules (Fig. 4C). No differences in the numbers of PLN DN iNKT cells was observed in standard NOD mice and those deficient in CD38 and/or P2X7 molecules (Fig. 4D). Although CD38-deficient mice have fewer iNKT cells, we previously showed that the remaining ones responded normally to α-GalCer stimulation (18). In this study, we also tested the function of CD38 and P2X7 double-deficient iNKT cells. On α-GalCer

FIGURE 5. Coablation of P2X7 improves the survival and function of Tregs in CD38-deficient NOD mice. The frequency of CD4 Tregs (CD25+Foxp3+) was determined in the spleens (A) and PLNs (B) of 10–11-wk-old male NOD mice and those deficient in CD38 and/or P2X7. A, The upper panel shows the representative CD25 and Foxp3 staining (gated on CD4 T cells). Results are summarized in the lower panel. *p < 0.05, compared with NOD mice (Mann–Whitney U test, n = 5–6 per genotype). B, The upper panel shows the representative CD25 and Foxp3 staining (gated on CD4 T cells). Results are summarized in the lower panel. *p < 0.05, compared with NOD mice (Mann–Whitney U test, n = 5–6 per genotype). C–E, In vitro Treg assay comparing the suppressive activity between indicated strains (age-matched female mice at 6–8 wk). NOD effector T cells (CD4+CD25−) were labeled with CFSE and cocultured at indicated ratios with Tregs (CD4+CD25+) in triplicate in a 96-well plate in the presence of NOD.scid splenocytes (2 × 10⁵) and 5 μg/ml anti-CD3 for 3 d. Proliferation of effector T cells was determined by CFSE dilution. The percentage of suppression is defined by the reduction in the proportion of divided effector T cells relative to that of the control without Tregs. Results indicate the mean ± SEM of three independent experiments.
stimulation, iNKT cells in standard NOD mice and the stock deficient in both CD38 and P2RX7 responded similarly as determined by intracellular IFN-γ and IL-4 staining (data not shown).

**FIGURE 6.** Identification of an NOD T1D susceptibility genetic locus closely linked to Cd38 on chromosome 5. A. Genetic map showing the Cd38 and P2rx7 congenic regions in the indicated strains. The physical locations of the markers/gene are based on NCBI Build 37. NA, not available. B. TID incidence of female NOD mice and stocks deficient in CD38 and/or ART2 molecules. *p < 0.005, compared with NOD mice (Kaplan–Meier log-rank analysis).

compared with those in standard NOD mice (Fig. 5C). Although P2X7 deficiency alone did not alter the suppressive activity of Tregs (Fig. 5D), it completely reversed the defect of those from CD38-deficient NOD mice (Fig. 5E versus 5C). These results indicate that the impaired function of Tregs in CD38-deficient NOD mice depends on the presence of intact P2X7 molecules.

A locus closely linked to CD38 regulates T1D development

We previously showed that further depletion of the iNKT and Treg compartments apparently contributing to accelerated T1D development in NOD.CD38−/− mice depended on the expression of ART2 molecules (17, 18). Together with the results reported in this study, we concluded that the further loss of iNKT cells, particularly the CD4+ subset, and Tregs in NOD.CD38−/− mice are due to P2X7-dependent NICD. However, in contrast with the observation in this study that codepletion of CD38 and P2X7 did not alter the rate of T1D onset in NOD background mice, disease development was strongly suppressed in a previously reported stock lacking both CD38 and ART2 (denoted as NOD.CD38−/−<long >.ART2−/− in this study) (17). This suggested that, in the absence of both CD38 and ART2-mediated NAD-degrading activities, increased levels of extracellular and/or intracellular NAD may exert T1D suppressive effects. It was also possible that a 129/Sv or C57BL/6 (B6)-derived T1D resistance gene(s) closely linked to the targeted Cd38 and/or Art2 alleles was inadvertently introduced into the previously reported NOD DKO stock during the backcrossing process. The latter possibility is supported by a recent study identifying a novel 129/Sv-derived T1D resistance locus on chromosome 5 in close linkage to the Cd38 gene (28). To test these possibilities, we used the currently reported NOD.CD38−/− mice with a shortened congenic interval (Fig. 6A) to generate a new stock lacking both CD38 and ART2 (denoted as NOD.CD38−/−<short >.ART2−/−) and monitored them for T1D development. It should be noted that the chromosome 5 congenic interval carrying the P2rx7 targeted allele does not overlap the 129/Sv and/or B6-derived region linked to the ablated Cd38 gene present in the original NOD.CD38−/−<long >.ART2−/− stock (Fig. 6A).

Consistent with previous results, NOD.CD38−/−<long >.ART2−/− stocks were respectively more susceptible or resistant to T1D compared with standard NOD mice (17) (Fig. 6B). Also as shown previously, ART2 deficiency alone did not alter the course of T1D development in NOD mice (17) (Fig. 6B). Interestingly, the newly generated NOD.CD38−/−<short >.ART2−/− stock displayed a similar T1D incidence as standard NOD mice (Fig. 6B). Collectively, these results indicate that T1D resistance observed in NOD.CD38−/−<long >.ART2−/− mice is largely due to the presence of a 129/Sv- and/or B6-derived disease protective gene(s) closely linked to the inactivated Cd38 allele.

Discussion

A P2X7 receptor variant has been previously suggested as a candidate T1D susceptibility gene in NOD mice (16). In this study, we found that P2X7 deficiency alone does not alter T1D development in NOD background mice. However, P2X7 is required to promote the accelerated rate of T1D onset characterizing NOD.CD38−/− mice. This was demonstrated by the finding that a newly generated NOD.CD38−/−.P2X7−/− stock developed T1D at the same rate as standard NOD mice. In the T cell compartment, CD4+ iNKT cells and Tregs are highly sensitive to P2X7-dependent ATP or NICD (18, 22). Although tight control mechanisms normally do not allow plasma ATP and NAD to reach levels sufficient to activate P2X7-mediated cell death, local concen-
trations of these small molecules could be significantly increased as a result of inflammation or tissue destruction (29). Indeed, it has recently been shown that high concentrations of extracellular NAD depleted Tregs in vivo and promoted immunogenic responses (30). Therefore, it is tempting to speculate that the suboptimal survival of Tregs in inflamed pancreatic islets in NOD mice is, in part, due to P2X_{2r}-dependent NICD in addition to the previously reported reduction in IL-2/IL-2R signaling (31). As a result of intraislet Treg loss, the pathogenic functions of β cell-specific effector T cells are further unleashed, possibly through enhanced accumulation of islet infiltrated and fully activated dendritic cells (32). Activated T cells shed ART2 molecules and become resistant to NICD (33). Therefore, P2X_{2r}-dependent NICD can also promote effector T cell activity by eliminating bystander naïve T cells that express high levels of ART2 (29). P2X_{2r} receptors can also regulate T cell activation directly. It has recently been demonstrated that stimulated T cells release ATP, which, in turn, stimulates P2X_{2r} molecules in an autocrine fashion to further promote their activation (5, 6).

The previously reported findings described earlier would seemingly have predicted suppressed T1D development in NOD.P2X_{2r}^{−/−} mice, a result that was not observed. In contrast, the P2X_{2r}-dependent cell death induction mechanism may also limit the initial activation of effector T cells. It has been reported that exacerbation of experimental autoimmune encephalomyelitis in P2X_{2r}-deficient mice is associated with reduced lymphocyte apoptosis in the inflamed tissues (34). Therefore, it is possible that pathogenic T cells remain susceptible to P2X_{2r}-dependent T cell death induction during the initial phase of their activation after encountering self-Ags and before shedding of ART2 molecules. Lack of P2X_{2r} may allow β cell autoreactive T cells to escape from this tolerance induction mechanism that normally limits the extent of self-reactivity. In this case, one would predict accelerated T1D onset in NOD.P2X_{2r}^{−/−} mice. However, our results demonstrate that T1D development in NOD.P2X_{2r}^{−/−} mice is not altered. It is possible that a combination of multiple T1D-promoting and -suppressing functions of the P2X_{2r} receptor on various cell populations in NOD mice masks its regulatory effects in this disease model.

In the absence of CD38 molecules, the balance is tipped toward favoring the proinflammatory functions of P2X_{2r} receptors as a result of increased extracellular levels of NAD. At the cellular level, the most apparent outcome of CD38 deficiency on the NOD background is the loss of CD4^{+} iNKT cells and Tregs, which, in turn, contributes to accelerated T1D development in these mice. Both NOD.CD38^{−/−}.P2X_{2r}^{−/−} and NOD.CD38^{−/−}.ART2^{−/−} exhibited similar T1D levels as standard NOD mice, indicating an important role of NICD in the regulation of disease development. In addition, increased levels of extracellular NAD may also increase ADP ribosylation of P2X_{2r} receptors on macrophages, which, in turn, promotes their production of the proinflammatory cytokine IL-1β (4).

In this study, we also demonstrated an NOD-derived T1D susceptibility locus closely linked to the Cd38 gene. The most apparent candidate region to harbor this T1D susceptibility locus is defined by the Cd38 gene (44.3 Mb) and the microsatellite marker D5Mit259 (89.7 Mb) (Fig. 6A). However, we could not rule out the possibility that the region proximal to the Cd38 gene was also truncated but not revealed by the markers used to define the congenic region. This possibility is supported by the discovery of a 129/Sv-derived T1D resistance locus with the logarithm of odds score peaking at 31 Mb, proximal to the Cd38 gene, in a previous quantitative trait locus analysis (28). Therefore, the location of this T1D susceptibility gene(s) reported in this study can be defined only by the markers D5Mit255 (36.6 Mb) and D5Mit259 (89.7 Mb). It is also possible that the congenic region carrying the Art2 mutant allele on chromosome 7 was also truncated without being revealed by the microsatellite markers used to type the interval in the newly generated NOD.CD38^{−/−}.ART2^{−/−} mice. However, this is not likely to be the reason the newly generated NOD.CD38^{−/−}.ART2^{−/−} stock became T1D susceptible in contrast with the marked T1D resistance in the previously reported DKO line. This is because NOD.ART2^{−/−} and standard NOD mice developed T1D at the same rate, indicating the 129/Sv-derived congenic region carrying the Art2 mutant allele alone does not suppress disease development. In addition, no 129/Sv T1D resistance loci were found on chromosome 7 in the previously reported QTL analysis (28).

In conclusion, we demonstrated that P2X_{2r} deficiency alone does not alter T1D incidence in NOD mice. However, T1D acceleration in NOD.CD38^{−/−}.ART2^{−/−} mice requires intact P2X_{2r} molecules. Similarly, expression of ART2 is also essential for accelerated T1D development in CD38-deficient NOD mice. Collectively, these results indicate an important role of NICD in the regulation of T1D in NOD mice. Our study also provides an example of how molecules in the same pathway can interactively modulate T1D development.

Acknowledgments
We thank Brenice Timms and Pam Stanley for technical assistance.

Disclosures
The authors have no financial conflicts of interest.

References


