Differential Impact of Costimulation Blockade on Antigen-Activation of Foxp3-Positive and Negative T Cells in A Model of Type 1 Diabetes

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Abstract

Using co stimulatory blockade to prevent activation and activity of beta cell specific effector T cells is a promising approach for preventing or reversing Type 1 diabetes (T1D). Regulatory T cells are likely critical for the maintenance of long-term tolerance. At present, it is unclear how co-stimulatory blocking agents affect the activity of regulatory T cells. To better understand the mechanism of costimulation blockade induced tolerance in murine autoimmune diabetes, we evaluated the effect of CD28 and CD154 blockade on both beta cell specific effector and regulatory T cell responses.

Diabetes transferred by lymphocytes isolated from BDC2.5.NOD mice could be prevented if cells were antigen-activated ex vivo in the presence of CTLA4Ig and anti-CD154. Following antigen-stimulation, both effector (Teffs; FoxP3-) and regulatory (Tregs; FoxP3+) CD4+ T cells upregulated CD25; divided and accumulated. Co-culture with CTLA4Ig and anti-CD154 dampened the quantitative and qualitative Teff response (i.e. cell cycling and CD25 expression), but there was little effect on the Treg response. Adding exogenous IL-2 to such cultures reversed the diabetes protective effect of CD28/CD154 blockade.

These findings suggest that Tregs do not only respond vigorously to antigen, but they rely less on traditional co-stimulatory signals than Teffs. Understanding the different signaling requirements of Teff and Tregs may facilitate the development and investigation of rational therapeutic interventions in Type1 diabetes that will both quiet diabetogenic effector T cells and enhance regulatory pathways.

Keywords: Type 1 diabetes; Regulatory T cells; Immune tolerance; NOD mouse; Costimulation

Abbreviations: CoB: Costimulation Blockade; T1D: Type 1 Diabetes; NOD: Non-Obese Diabetic; MHC: Major Histocompatibility Complex; NRT: Non-Regulatory T cells

Introduction

In many animal models of allo- and auto-immune, immune tolerance can be generated by the administration of agents that interfere with T cell activation. Unfortunately, this has not translated to a successful approach for tolerance induction in humans. In the case of T1D, the concept of using a brief course of immunotherapy to quiet diabetes effector T cells and engendering immune tolerance is one of the most attractive approaches for disease prevention or reversal. One of the most reliable means to prevent autoimmunity and allograft rejection in rodents is by interfering with the CD28/B7 and CD154/CD40 T cell co-stimulatory pathways [1-4]. Although this approach is successful in inducing tolerance in a vast array of models and conditions, the precise cellular mechanisms involved in subduing effector T cells and maintaining a nonpathogenic state is unclear. For transition of a quiescent in to a effector T cell, T cells must receive signal 1 from T cell receptor engagement and a second signal via co-stimulatory or accessory molecule engagement, and without this second signal T cells are susceptible to deletion or long-term deactivation (i.e. anergy) [1,5-8]. Although helpful in identifying the roles and pathways of costimulatory molecules, the in vitro findings may not accurately reflect the precise in situ roles of these molecules or the consequence of targeted blockade during antigen presentation by antigen presenting cells. In addition different T cell subtypes (i.e. CD4 vs. CD8 and naïve vs. memory cells) appear to have different requirements and thresholds for signal 1 and signal 2. Therefore it may be difficult and unwise to assume how an intervention may affect one T cell subtype based on findings from another.

Type 1 diabetes (T1D) is a T cell mediated autoimmune condition and the expression disease appears to be influenced, at least in part, by the balance of beta cell recognizing effector and regulatory T cells [9-11]. Beta cell-specific autoreactive cells that have escaped central tolerance become activated and are responsible for beta cell destruction. A number of defects in peripheral tolerance are thus also implicated in diabetes pathogenesis, including, deletion and deactivation (i.e. anergy) of autoreactive T cells and modulation by regulatory T cells.

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[9,11]. Many studies indicate that diabetes is the result of quantitative or qualitative deficiencies in regulatory T cells, and, conversely, treatment with regulatory T cells can prevent diabetes in animal models of T1D. Tregs may be derived from thymic precursors or evolve from peripheral non-regulatory T cells, and the circulating pool appears to be maintained through interactions of self peptide: MHC complexes. The suppression of effector responses by Tregs can occur via both cell-cell interaction and as a result of soluble mediators, which may depend on the site and type of antigen encounter [10,12,13]. Although there is a vast knowledge of the requirements, processes, and pathways for effector cell activation, it is less well understood how Treg function is modified during times of stimulatory antigen-encounter and how Treg numbers and function may be influenced by costimulation blockade therapies.

In our previous studies, we found that we could prevent the adoptive transfer of autoimmune diabetes by highly pathogenic BDC2.5.NOD CD4+ T cells by a short course of in vivo therapy of interfering with CD28 and CD154 (CTLA4-Ig and antiCD154), and that this protection was a result of non-deletional, regulatory tolerance [14]. Our data suggested that this approach induces immune tolerance through dampening antigen specific expansion of effector T cells while permitting regulatory T cells to become established, providing β cells both immediate and long-term protection from diabetogenic T cells. In order to better understand how the outcome of an immune response can be altered by blocking select T cell signaling pathways, the goal of this current study was to better define how effector and regulatory T cells respond to antigen and how these responses can be modified by agents that are capable of tolerance induction.

Materials and Methods

Mice

BDC2.5.NOD (BDC.NOD) and nod.scid mice were from on site breeding colonies bred and housed in sterile conditions. BDC.NOD mice were defined via blood phenotype containing B220+ cells and CD3+ cells that were uniformly vβ4+. Studies were conducted in accordance with the Emory University Institutional Animal Care and Use Committee guidelines.

Antibodies

Fluorochrome-conjugated monoclonal antibodies to CD3, CD4, vβ4, B220, CD62L, CD25, flow cytometry were from BD Biosciences/Pharmingen. Anti-FoxP3 staining kits were from eBiosciences. Anti-CD154 (MR1) and CTLA4-Ig used in in vitro cultures were from BioExcel (West Lebanon, NH).

Cell preparation and culture

BDC.NOD mice were euthanized and spleens and lymph nodes harvested and made into cell suspensions, and washed in RPMI. Cells were adjusted to 1-2 million cells/ml in RPMI + 10% FCS and were added to flat bottom cell culture plates (Falcon). When indicated, stimulatory peptide (10 μg/ml; RTRPLWVRME; Emory University Microchemical facility [15], CTLA4-Ig (100μg/ml) and/or anti-CD154 (1000μg/ml; MR1)) was added. Cells were incubated at 37°C in a humidified incubator containing 5% CO2 for times indicated in the text. For fluorescent labeling, prior to culture, cells were incubated with 5 μmol/l carboxyfluorescein succinimidyl ester (CFSE, BD Biosciences) at 37°C ×10 min, quenched with cold RPMI+10% FCS, and washed using an inverted microscope (Olympus IX70). Still shots were taken with a fitted with a Polaroid DMC2 digital camera and processed with the supplied software.

Flow cytometry

For qualitative analysis, freshly isolated cells or cultured cells were incubated with directly conjugated antibodies to cell surface molecules for 20 min, and then processed per the manufacturer’s instructions for intracellular FoxP3 detection. Cells were then run on an LSRII (BD Biosciences) and data analyzed with FlowJo (TreeStar). Cells cultured in media and stained with directly conjugated antibodies were used to establish gating. For quantitative flow cytometry, prior to or during culture, cells were resuspended, 100 μl removed and added to a TruCount Tube, containing 5 μl each of surface antibodies and vortexed. After 20 min incubation, 100 μl of stabilizing fixative (BD Biosciences) was added and samples evaluated by flow cytometry. A conversion factor was calculated by dividing the bead number in the tube supplied by the manufacturer by the final volume in the tube (i.e. 225 μl). Following analysis, a ratio of cells to beads was determined. Absolute cell numbers were calculated by multiplying this ration by the conversion factor. For CFSE evaluation cells cultured as indicated were assessed by flow cytometry and CD3+, CD4+, T cells were grouped into either FoxP3+ or FoxP3- subpopulations. CFSE peaks were manually determined and used as a gating strategy for other samples in the same individual experiment.

Adoptive transfer and diabetes detection

For adoptive transfer cells were prepared as above and cultured in the absence or presence of stimulatory peptide (10 μg/ml), CTLA4Ig (100 μg/ml), MR1 (100 μg/ml) and/or rIL-2 (500 IU/ml). After 4 days in culture, contents of the wells were resuspended, washed twice in RPMI media, and injected via lateral tail vein into NOD.SCID mice. Tail vein blood was analyzed using a Bayer Ascensia Elite Glucometer three times weekly. Diabetes was diagnosed at the first of two consecutive readings >250 mg/dl.

Cytokine evaluation

During cell culture, supernatant was removed from wells without disturbing cells. IL-2 content was quantitated using a murine bioplex cytokine assay (BioRad) analyzed on a Luminex 100 IS system according to the manufacturer’s instructions.

Statistical Analysis

Where indicated Student’s t-test or Fisher’s Exact test were used to compare statistical significance. Where multiple comparisons were to be made, ANOVA or exact contingency table analysis was conducted first with post-hoc comparisons of individual groups.

Results

We have previously demonstrated that in vivo treatment with CTLA4Ig and anti-CD154 to block the CD28/B7 and CD154/CD40 pathways can prevent diabetes in nod.scid adoptive transfer recipients of diabeticogenic BDC cells. To determine if costimulation blockade could also influence the pathogenicity of ex vivo antigen activated T cells, BDC cells were incubated with stimulatory peptide in the absence or presence of stimulatory peptide (10 μg/ml), CTLA4-Ig and antiCD154, and then transferred into NOD.SCID mice (Figure 1). Recipients of cells incubated with or without stimulatory peptide reliably developed diabetes. Diabetes development was minimally impacted when peptide stimulation occurred with anti-CD154 treatment alone and somewhat...
slowed by CTLA4Ig alone. Yet the recipients of cells antigen-activated in the presence of both CTLA4Ig and anti-CD154 (combined costimulation blockade (cCoB)) were regularly protected from diabetes. This data suggests that the previously observed in vivo tolerogenic effects of combined CD28/CD154 blockade can be recapitulated during antigen-specific encounter in vitro.

To investigate the effect of costimulation blockade on the activation of T cells by specific antigen, BDC cells were incubated for up to 4 days in the absence or presence of stimulatory peptide, with or without individual or combined costimulation blockade and evaluated. T cells incubated with peptide with or without combined blockade underwent blast transformation and clumping consistent with activation (Figure 2). When CD4+ T cell accumulation was assessed by quantitative flow cytometry, in all culture conditions that contained stimulatory peptide, there was substantial expansion of total CD4+ T cells (Figure 3). In the presence of costimulation blockade, total T cell numbers were reduced to 50-60% of maximum numbers seen with peptide-only stimulation. Total T cell expansion was not noticeably affected by anti-CD154 alone and intermediately reduced by CTLA4Ig alone (data not shown). These data indicate that, even in the presence of agents that interfere with pathways considered integral for T cell activation, T cells may still go through some of the early processes associated with activation (i.e., blast transformation and proliferation) following specific antigen encounter.

Altering the balance of effector and regulatory T cells can influence diabetes susceptibility or protection. In BCD2.5.NOD mice approximately 10-15% of CD4+ T cells are FoxP3+ regulatory T cells (Tregs). We examined how regulatory and non-regulatory T cell subpopulations were affected by stimulatory antigen and costimulation antagonism. Following antigen stimulation, in terms of absolute numbers, both non-regulatory T cells (NRTs) and Tregs expanded substantially from baseline numbers in all conditions containing stimulatory peptide (Figure 3). Yet there was a relatively higher accumulation of NRTs over Tregs with peptide stimulation demonstrated as a lower percentage FoxP3+ cells compared to input cells. In the presence of combined costimulation blockade (Figure 3), maximal NRT numbers were significantly and substantially reduced, whereas there was actually an increase in Treg numbers, resulting in a relatively higher percentage of Tregs. This data suggests that in response to antigen-specific stimulation, CD28/CD154 blockade relatively specifically retards the expansion and development of effector cells with a minimal quantitative effect on Tregs expansion. The net effect of combined blockade during antigen stimulation is a higher Treg to Teff ratio than with antigen stimulation alone.

We then assessed how costimulation blockade affected the initial proliferative responses of antigen activated T cell subpopulations by CFSE content (Figure 4). One day following antigen exposure (Figure 4a), cell cycling had not begun; yet by day 3 (Figures 4a and 4b), the majority of NRTs and Tregs had gone through several divisions. At day 3, with peptide stimulation only, more NRTs had gone through a greater number of divisions than Tregs. For example, as shown in histograms (4a) and graphically (4b), although most NRTs and Tregs have had at least 1 division, approximately 40% of NRTs have gone through at least 4 divisions, compared to ~15% of Tregs. Costimulation blockade appeared to preferentially dampen the intermediate cycling of NRTs. At day 3 almost all (>90%) NRTs stimulated in the presence of CoB have gone through at least 1 division, yet a minority (i.e. ~20%) of cells has gone through 4 or more divisions (Figures 4a and 4b). In sharp contrast, the division kinetics of peptide stimulated Tregs is not noticeably altered by costimulation blockade (Figures 4a and 4b).

Figure 1: Adoptive transfer of in vitro, peptide-activated BDC cells can be prevented by co-culture with CTLA4Ig and anti-CD154. Lymphocytes were harvested from BDC2.5.NOD mice and cultured for 4 days in the absence or presence of stimulatory peptide with or without CTLA4Ig and/or anti-CD154. 2.5 x 106 cells were then transferred intravenously to nod scid recipients that were followed for diabetes. Cx only = cells cultured alone without peptide. CTLA4Ig or anti-CD154. CoB = the combination of costimulation blockade agents, CTLA4Ig and anti-CD154. p < 0.001 when comparing diabetes rates at 7 weeks in peptide only, peptide+CTLA4ig, and peptide+CoB groups using exact contingency table analysis. In post-hoc Fisher exact test analysis, p < 0.001 (*) and p = 0.026 (†) comparing diabetes rates in peptide only group to peptide+CoB or peptide+CTLA4ig groups respectively.

Figure 2: Peptide-stimulated BDC cells are activated in the presence of CTLA4Ig and anti-CD154. BDC cells were cultured for 3 days in the absence (culture (Cx) only) or presence of stimulatory peptide without (Peptide Only) or with CTLA4Ig and anti-CD154 (combined costimulation blockade (cCoB)). Photomicrographs of cultured cells were taken (left panel). In addition cells were stained with CD3, CD4 and vβ4- fluorochrome-conjugated antibodies. CD3+, CD4+ and vβ4+ cells were identified via flow cytometry (where vβ4+ cells were regularly >90% of the CD3+, CD4+ population) and the side-scattered (SSC) versus vβ4 cells are shown (right panels). Peptide stimulate cells even in the presence of costimulation blockade go through some of the processes of activation, including blastogenesis and clumping. Shown are representative of more than 6 experiments.
The results thus far suggest a selective, quantitative dampening effect of costimulation blockade on the generation of Teffs over Tregs. We next asked if there were qualitative repercussions of costimulation blockade on developing effector and regulatory T cells. CD25 is the alpha component of the IL-2 receptor complex, and is rapidly upregulated during T cell activation and integral to T cell expansion and differentiation. Wells et al. has demonstrated that interfering with CD28 signaling (using CTLA4Ig) during polyclonal stimulation of T cells slows cell division and reduces CD25 expression [16]. CD62L is an adhesion molecule expressed primarily by naïve T cells, assists with lymph node trafficking and is shed following activation. We assessed CD25 and CD62L expression on NRT and regulatory cells before (Figure 5a) and at different division stages following peptide activation in the absence and presence of costimulation blockade (Figures 5b and 5c). At 24 hours, before any division has occurred, CD25 is highly upregulated on virtually all NRTs and Tregs cultured with peptide, regardless of division stage (i.e. CFSE content). After 3 days, CD25 expression remains highly expressed on NRTs and Tregs stimulated in the presence and absence of costimulation blockade (Figure 5a) and at different division stages following peptide activation in the presence and absence of costimulation blockade (Figures 5b and 5c). At 24 hours, before any division has occurred, CD25 is highly upregulated on virtually all NRTs and Tregs cultured with peptide, regardless of division stage (i.e. CFSE content). Conversely CD25 expression on RTs substantially reduced on antigen-activated NRTs cultured with costimulation blockade. When CD25 expression is plotted according to divisional stage at day 0, 1, and day 3 (Figure 6) it’s clear to see that CD25 increases on Tregs and remained highly expressed on the day of division stage following antigen encounter, irrespective of the addition of CTLA4Ig and anti-CD154 (Figure 6 solid lines). In sharp contrast, on NRTs activated in the presence of combined costimulation blockade, CD25 expression peaks but then is sequentially diminished over time with progressive cell divisions (Figure 6 dashed lines).

In comparison, there was no apparent regular selective impact of costimulation blockade on CD62L expression on NRTs or Tregs during activation (Figure 5c).

IL-2, produced either in an autocrine or paracrine manner, is integral in the activation and expansion of effector T cells. TCR and costimulatory signals promote expression of the IL-2R and IL-2 transcription [17]. To investigate the effect of costimulation blockade on IL-2 production in our model, we assessed IL-2 levels in culture supernatants of cells activated in the presence and absence of costimulation blockade (Figure 7a). As expected, with peptide stimulation alone IL-2 was found in abundance in supernatants 2 days following stimulation. By day 3, IL-2 levels were radically diminished in these cultures which likely reflect IL2 consumption in the expanding cells and/or the negative feedback of IL2 production to prevent uncontrolled T cell expansion. Little IL-2 was detected on any day in non-stimulated cultures or those stimulated in the presence of combined blockade despite significant turnover of both NTR and Tregs.

To ascertain if reconstituting IL-2 could reverse protective effects of combined blockade on ex vivo stimulated cells, BDC cells were peptide-stimulated in the presence of combined blockade and exogenous IL-2 (Figure 7b). Adoptive transfer recipients of these cells uniformly developed diabetes at a rate and tempo similar to recipients of cells stimulated with peptide alone.

**Discussion**

In this report we find that we can prevent the diabetogenicity of ex vivo antigen activated BDC T cells by concomitant blockade of the CD28 and CD154 pathways. Similar to ours in **ex vivo** model, ex **vivo** blocking either pathway alone is less effective and reliable than combined blockade. It is known from a variety of allo- and autoimmune models that these two immunosuppressive agents can cooperate in a unique manner in to suppress effector T cell response and produce a state of long-lasting immune protection. Despite these multiple observations, relatively little is known of the immunologic processes responsible for this effect. What this work provides is important mechanistic insight as to how antigen activated effector and regulatory T cells appear to be differentially affected by CD28/CD154 blockade. CD28 was one of the first costimulatory molecules described, as cross-linking with TCR
CD80 and CD86, can impair allo and auto-immune responses in non-T cells. On the other hand, CTLA4Ig and antagonistic antibodies to indicate that CD28 is not always required for the generation of effector mice are quite capable of orchestrating the destruction of beta cells to the absence of regulatory T cells, the fact that T cells from these an early age [9,21]. Although this high incidence of diabetes is linked generating an effective T cell response. Yet from some induced T cell proliferation [7,11,18-20]. Due to the findings from such in vitro studies, CD28 signaling is often considered “requisite’ for such studies, CD28 signaling is often considered “requisite’ for

knockout models [3,22-26]. Currently CTLA4lg (Abatacept) which is FDA approved for rheumatoid arthritis, has shown success in juvenile idiopathic arthritis, and has shown promise in newly diagnosed T1D [1,4,27]. A sequence variant of CTLA4lg, LEA29Y (Belatacept) is in clinical trials for transplantation [4,27,28].

CD154 also integral to the T cell response and is induced on T cells following TCR engagement and binds to CD40 constitutively expresses on APCs. Anti-CD154 alone can delay alloagraft rejection and autoimmunity and NOD CD154-knockout mice are nearly fully protected from diabetes [29-32]. Due to its small cytoplasmic domain,
it is unclear to what extent CD154 directly participates in T cell activation, but blocking may interfere with cognate B cell and dendritic cells [1,33,34]. Clinical evaluation of blocking the CD154 pathway was derailed because anti-CD154 can lead to thromboembolism, likely secondary platelet activation [1,35]. Identifying alternative means to interfere with the CD154/CD40 pathway (i.e. targeting CD40 and alternative CD154 blockers) are being actively investigated [1,27]. Further study of this pathway is therefore important and justified.

Despite many studies utilizing these approaches to quiesce immune responses, relatively little is known about the effects of CD28 and CD154 blockade affects in normal T cell responses and can lead to immune tolerance. Wells et al. [36] demonstrated that although T cells in bulk splenocytes do proliferate with anti-TCR monoclonal antibody, cell division can be accelerated with agonistic anti-CD28 and dampened (but not eliminated) using CTLA4Ig (16). In these studies, CD25 was upregulated most abundantly on anti TCR + anti CD28 stimulated T cells and lowest on in those cultured with anti-TCR and CTLA4Ig and supplementation with exogenous IL-2 in the CTLA4g containing cultures restored CD25 expression and proliferation. In subsequent studies, they concluded that “anergy” (as defined by resistance to subsequent stimulation) may take place following TCR and CD28 stimulation if cells fail to proliferate or when TCR receptor ligation occurs in the absence of CD28 signaling irrespective of proliferation. Although such studies have greatly assisted in evaluating the role of costimulation in T cell activation and expansion, it still remains unclear how interfering with select costimulatory pathways affects select T cell

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Figure 6: Kinetics of CD25 expression of non-regulatory and regulatory T cells of cells activated in the absence and presence of costimulation blockade. CD25 was assessed by CFSE under the conditions shown. Shown are results from one of 3 independent experiments.
We find that Tregs respond to antigen encounter in man relatively passive during the early phases of an immune response. Many consider Tregs to be minimally responsive to antigen and are T cell and (pre) effector T cell subpopulations (that we refer to as "non-activated T cells in an animal model of autoimmune diabetes, and focus on how this intervention effects Teff and Treg responses.

Figure 7: IL-2 is suppressed in BDC cultures stimulated in the presence of costimulation blockade and reconstitution re-engenders diabetogenicity. (A) BDC cells were cultured in the absence or presence of stimulatory peptide with or without CTL4Ig and anti-CD154. At 1, 2, and 3 days a sample of supernatant was removed and quantitated for IL-2. Shown are the mean IL2 Levels and standard deviation from 3 independent experiments. ANOVA then post hoc Student’s t-Test (p values displayed) was conducted to compare IL2 levels on day 1 vs. 2 and day 2 vs. 3 on the peptide only cultures. (B) Exogenous IL-2 was added to BDC cells cultured in the presence of stimulatory peptide and CTLA4Ig and anti-CD154, then 2.5 x 10^6 cells were intravenously transferred to nod.scid mice that were serially assessed for diabetes. For comparison shown are also the results of recipients of cells stimulated in the presence of combined costimulation blockade. Fisher's Exact test was used to compare diabetes incidence at 7 weeks.

In this report we believe we are the first to report that combined CD28/CD154 blockade suppress the pathogenicity of ex vivo antigen-activated T cells in an animal model of autoimmune diabetes, and focus on how this intervention effects Teff and Treg responses.

We compared both qualitatively and quantitatively how regulatory T cell and (pre) effector T cell subpopulations (that we refer to as “non-regulatory” T (NRT) cells) respond to the same antigenic challenge. Many consider Tregs to be minimally responsive to antigen and are relatively passive during the early phases of an immune response [37,38]. We find that Tregs respond to antigen encounter in many ways like NRTs. In response to antigen-encounter, Tregs promptly upregulate CD25 (even before division) and divide and accumulate over time. Comparatively, slightly more NRTs appear to cycle than Tregs, and more NRTs divided to greater extent than Tregs – which may be responsible for the greater expansion of NTR. Yet additional factors such as greater activation induced death in the Treg population may also impact the final cell numbers. Therefore although there may be some "absolute" differences in the way Teffs and Tregs respond to antigen (i.e. production of IL-2), there appear to be some responses that are nearly indistinguishable (i.e. rapid regulation of CD25) and some that differ in degree (i.e. proliferation, cell accumulation, activation induced death). Despite similarities in antigen responsiveness, the degree of the robustness of the proliferative response to a specific antigen appears to be greater in NRTs than Tregs. This inherent stochastic advantage of the inherent Teff response to "stimulatory" antigen may favor the activation and accumulation of Teffs over Tregs, and therefore pathogenesis.

Although the default immune response to certain "stimulatory" antigens may be Teff “predominant” (and thus pathogenic), our findings suggest that effector T cells and Treg have different costimulatory requirements and therefore the outcome of antigen encounter may be modifiable by agents that interfere with accessory T cell signals.

Specifically our findings suggest that the activation and generation of Tregs is significantly less dependent on CD28 and CD154 than Teffs. In our study, we confirm and extend previous results that CTLA4Ig dampens the proliferative response of TCRengaged T cells. We demonstrate that CTLA4Ig alone or in combination with anti-CD154, suppresses the division and accumulation Teffs, and impairs the pathogenicity of these cells. In contrast, costimulation blockade has little impact on the division, expansion, and accumulation of antigen-activated Tregs. Therefore CD28 antagonism, and to a greater extent combined CD28/CD154 blockade, appears to directly influence the net balance of the number Teff and Tregs following activating antigen exposure. It is well known that CD154 blockade, alone or in combination, can prevent or delay allo- or autoimmunity in animal models. Interestingly we find that independent blockade of CD154 has neither substantial impact on the division nor accumulation of NRTs or Tregs following antigen stimulation. CD154 blockade alone nominally reduces IL-2 production and augments CD28 blockade depression of IL-2 production and CD25 expression. Although CD154 has been defined as one of the significant T cell costimulatory molecules, its blocking has little effect on many of the outcomes usually associated with activation (i.e. T cell proliferation). This may suggest that during normal immune responses CD154 is involved with aspects of T cell activation other than proliferation (i.e. cytokine production) or effect other facets of the immune response, for example CD40-mediated APC maturation or activation. The fact that immuno-modulatory agents which may have powerful in vivo effects may minimally impact select in vitro readout of T cell activation (i.e. proliferative), may suggest that these assays may not serve as effective screening methods to identify clinically important immunosuppressive or tolerance induction agents.

In addition to affecting the quantitative balance of Teffs and Treg following antigen encounter, costimulation blockade appears to selectively suppress functional aspects of effector T cells. CD25 is the alpha component of the high affinity IL-2- receptor, and its expression is increased on T cells following TCR receptor engagement and allows responsiveness to IL-2. Signaling through the IL-2 receptor is considered a prerequisite for the propagation of an effective immune response. Studies from Wells and others showed that CD25 expression...
can be blunted by CD28 blockade on bulk TCR stimulated T cells [16,36]. We sought to further investigate the effect of CD28 and CD154 blockade on CD25 expression on antigen-specific CD4+ NRTs and Teffs. 24 hours following antigen encounter, regardless of co-culture with any agent, CD25 is highly upregulated on essentially all NRTs and Tregs, prior to division.

Although initial CD25 expression in all CD4+ T cells appears independent of costimulation blockade, maintenance of CD25 on NRTs requires CD28 and CD154 signaling. In NRTs, CD25 expression is maintained at high levels in each daughter division, yet CD25 levels are depressed in a division-dependent manner in cultures containing CD28 and CD154 blockade. T cell costimulation promotes IL-2 transcription and production, and IL-2 appears critical in the cell division and maintenance of CD25 expression on NRTs. Our studies suggest that IL-2/IL-2R independent division takes place through division 2 or 3, and then slows in the absence of IL-2. IL-2 appears to assist in maintaining the proliferative response in NRTs following this initial phase. Interestingly, we find little IL-2 in antigen-stimulated cultures at 4 days, suggesting that after such licensing continued expansion and differentiation of Teffs does not require IL-2.

In sharp contrast to the decrease of CD25 on NRTs stimulated in the presence of costimulation blockade, Tregs maintain high CD25 expression no matter their divisional stage. Therefore at the same time there are fewer absolute numbers of NRTs with lowered ability to expand, expansion and activation level of Tregs is relatively unaffected. This effect of costimulation blockade on surface molecule expression is not a generalized phenomenon, as CD62L on all cells is lost following antigen encounter, and then gradually re-accumulates with time and divisions, irrespective of cell type or the presence of costimulation blockade. As some of the very early steps of effector T cell generation occur in the presence of CD28/CD154 blockade (i.e. blastogenesis, clustering, CD25 expression and initial cell divisions), costimulation blockade appears to "abort" activation, rather than "preventing" activation or leading to certain cell death. When isolated, these NRTs that have undergone this "abortive activation" still retain the ability to transfer diabetes, and therefore are not rendered "terminally" non-pathogenic (data not shown). We postulate that these "abortively activated" NRTs have reduced immediate pathogenicity and are susceptible to suppression by Tregs.

Although Tregs do not produce IL-2, in some cases paracrine or exogenous IL-2 can drive the expansion of quiescent or TCR stimulated Tregs. Yet our work suggests that Treg proliferation may be less dependent on IL-2 than emerging Teffs or in fact may occur independent of IL-2. In our study, IL-2 is detected at high levels in antigen-only stimulated cultures and minimally in cultures with costimulation blockade. In both of those culture conditions expansion and accumulation of Tregs is similar. One interpretation from this is that in situ, peripheral Treg activation and expansion following antigen encounter is critically dependent on CD28, CD154, nor IL-2. Although CD28 is critical in the thymic development of Tregs [10,39-41], this same pathway may not be integral in the function of established Tregs. This may seem to contrast the common notion that IL-2 and perhaps CD28 is needed for Treg expansion and function. Some of this belief may stem from the observation that regulatory T cell, in humans and rodent, appear to need CD28 signals for homeostasis, as blocking CD28 in non-activated cells or in vivo may reduce Treg numbers. In contrast, our study uses a highly stimulatory antigen, and may suggest that the need for certain costimulatory signals for Tregs is in part impacted by antigen avidity or potency.

In addition, anti-CD28 and exogenous IL-2 has been used to expand Treg ex vivo, but this does not necessarily repudiate our findings. In such approaches it is critical to pre-deplete NTR (i.e. CD3+, CD25 low) to prevent their overgrowth, suggesting that NTR are much more responsive to CD28 and IL-2 than Tregs [13,42,43]. Because CD28 and IL-2 can expand Tregs ex vivo, it does not mean CD28 or IL-2 are critical for in situ, natural, responses. We believe that in our model using a natural admixture of endogenous cells (including T and B cells, and APCs) and stimulatory antigen more closely resembles an in situ immune response versus the in vitro situation of stimulating sorted CD25+ T cells using non-selective approaches (i.e. anti-CD3). Therefore our study may provide novel insight as to how Teffs and Tregs respond naturally to highly stimulatory antigens in conditions like Type 1 diabetes.

Our findings may be consistent with how some others suggest peripheral Tregs are maintained and function. For example, following specific antigen-MHC encounter and in the absence of CD28/CD154 signaling), Tregs are able to survive and turnover, and therefore be maintained at a critical mass, even in low IL-2 environments. One putative mechanism by which Tregs suppress immune responses is due to their expression of CD25 (and therefore the high affinity IL-2 receptor), and allowing them to scavenge soluble IL-2 away from effector T cells when antigen- or NTR levels are limiting, and thus slow or prevent their activation, expansion, and pathogenicity [10,38]. Yet our study may suggest that during a more robust NTR response (due to higher antigen levels, TCR/MHC avidity or higher NTR precursor frequency) when IL-2 levels are higher, NTR expansion outpaces the suppressive capabilities of Tregs and the effector response predominates. Increasing Treg number and the level of high affinity IL-2 receptor complex on them following antigen-encounter during times of immune quiescence (i.e. non-“danger”) may be one means to increase the specificity and robustness of their regulatory response. The natural repertoire of Tregs is highly skewed to self-antigens [10,44,45]. If peripheral Tregs can expand and be maintained in an activated state in the absence of "traditional" costimulation (i.e. CD28, CD154, IL-2), this might be a means to retain a critical mass of T cells which help maintain self-tolerance and prevent autoimmunity. Therefore blocking select signals usually associated with an effective (i.e. pro-inflammatory) immune response may selectively subdue effector T cell generation while allowing the expansion of regulatory process, primarily functional Tregs.

The outcome of an immune response can be influenced by the balance of effector and regulatory T cells. In the case of autoimmune diseases, disease can be induced or prevented by altering the balance of diabetogenic or regulatory T cells [6,9,21,46]. We have developed a working model which integrates our current and previous findings regarding how costimulation blockade may affect effector and regulatory T cell responses to transform a pathogenic response into a protective one. Our data suggest that both pre-effector and regulatory cells can respond vigorously to antigen. With appropriate costimulation, the effector cell response outpaces the Treg response, and, in this model, beta cells are destroyed and diabetes ensues. In the presence of CD28 and CD154 blockade both the number and function of developing effector cells is dampened. By derailing the activation of Teffs, pathogenic effectors are not initially produced and the target tissues (beta cells) are spared. Because of different activation requirements Tregs still expand and function in the presence of blocking agents. The resultant Tregs maintains beta cell protection, and thus tolerance, by suppressing subsequent activation of effector cells. In this scenario costimulation blockade selectively limits the expansion
and activation state of developing Tregs and has little impact on the Treg response to antigen.

It is this relative change in the Teff-Treg balance that is enough to shift the outcome of a pathogenic response to a protective one.

In summary, we believe that this work provides added insight and an important new perspective to how effector and regulatory cells innately respond to specific antigen challenge. Specifically, we hypothesize that because circulating, mature effector and regular T cell have different absolute or relative (i.e. threshold) costimulation requirements, their expansion, function, and the clinical consequences of antigen encounter can be modified by agents the block select costimulatory pathways, both in vivo and ex vivo. Understanding how to manipulate these responses based on the signaling and the activation requirements of protective and pathogenic T cells could be instrumental in developing strategies which can be translated to control unwanted immune responses, such as Type 1 diabetes.

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References

1. Weaver TA, Charafe-Jauffret E, Kirk AD (2008) Costimulation blockade: towards clinical application. Front Biosci 13: 2120-2139.
2. Howard LM, Kohrn AP, Castaneda CL, Miller SD (2005) Therapeutic blockade of TCR signal transduction and co-stimulation in autoimmune disease. Curr Drug Targets Inflamm Allergy 4: 205-216.
3. Greenwald RJ, Freeman GJ, Sharpe AH (2005) The B7 family revisited. Annu Rev Immunol 23: 515-548.
4. Vincenti F (2008) Costimulation blockade in autoimmunity and transplantation. J Allergy Clin Immunol 121: 299-306.
5. Schwartz RH, Mueller DL, Jenkins MK, Quill H (1989) T-cell clonal anergy. Cold Spring Harb Symp Quant Biol 54: 605-610.
6. Rossini AA, Greiner DL, Mordes JP (1999) Induction of immunologic tolerance for transplantation. Physiol Rev 79: 99-141.
7. Mueller DL, Jenkins MK, Schwartz RH (1989) Clonal expansion versus functional clonal inactivation: a costimulatory signalling pathway determines the outcome of T cell antigen receptor occupancy. Annu Rev Immunol 7: 445-480.
8. Wells AD, Li XC, Strom TB, Turka LA (2001) The role of peripheral T-cell deletion in transplantation tolerance. Philos Trans R Soc Lond B Biol Sci 356: 617-623.
9. Bour-Jordan H, Salomon BL, Thompson HL, Szot GL, Bernhard MR, et al. (2004) Costimulation controls diabetes by altering the balance of pathogenic and regulatory T cells. J Clin Invest 114: 979-987.
10. Bour-Jordan H, Bluestone JA (2009) Regulating the regulators: costimulatory signals control the homeostasis and function of regulatory T cells. Immunol Rev 225: 41-66.
11. Mordes JP, Bortell R, Doukas J, Rigby M, Whalen B, et al. (1996) The B7/CD28/Wor rat and the balance hypothesis of autoimmunity. Diabetes Metab Rev 12: 103-109.
12. Bluestone JA, Tang Q (2005) How do CD4+CD25+ regulatory T cells control autoimmunity? Curr Opin Immunol 17: 638-642.
13. Brusko TM, Putnam AL, Bluestone JA (2008) Human regulatory T cells: role in autoimmune disease and therapeutic opportunities. Immol Rev 223: 371-390.
14. Rigby MR, Trexler AM, Pearson TC, Larsen CP (2008) CD28/CTLA-4 blockade prevents autoimmune diabetes by inducing nondeleterious tolerance after effector T-cell inhibition and regulatory T-cell expansion. Diabetes 57: 2672-2683.
15. Judkowski V, Pinilla C, Schroder K, Tucker L, Sarvetnick N, et al. (2001) identification of MHC class II-restricted peptide ligands, including a glutamic acid decarboxylase 65 sequence, that stimulate diabetogenic T cells from transgenic BDC2.5 nonobese diabetic mice. J Immunol 166: 908-917.
16. Wells AD, Gudmundsdottir H, Turka LA (1997) Following the fate of individual T cells throughout activation and clonal expansion. Signals from T cell receptor and CD28 differentially regulate the induction and duration of a proliferative response. J Clin Invest 100: 3173-3183.
17. Crispin JC, Tsokos GC (2009) Transcriptional regulation of IL-2 in health and autoimmunity. Autoimmun Rev 8: 190-195.
18. Rossini AA, Mordes JP, Greiner DL (1989) The pathogenesis of autoimmune diabetes mellitus. Curr Opin Immunol 2: 598-603.
19. Rossini AA, Parker DC, Phillips NE, Durie FH, Noelle RJ, et al. (1996) Induction of immunological tolerance to islet allografts. Cell Transplant 5: 49-52.
20. Herold KG, Lenschow DJ, Bluestone JA (1997) CD28/B7 regulation of autoimmune diabetes. Immol Rev 16: 71-84.
21. Salomon B, Lenschow DJ, Rhee L, Ashourian N, Singh B, et al. (2000) B7/CD28 costimulation is essential for the homeostasis of the CD4+CD25+ immunoregulatory T cells that control autoimmune diabetes. Immol 12: 431-440.
22. Lenschow DJ, Ho SC, Sattar H, Rhee L, Gray G, et al. (1995) Differential effects of anti-B7-1 and anti-B7-2 monoclonal antibody treatment on the development of diabetes in the nonobese diabetic mouse. J Exp Med 181: 1145-1155.
23. Larsen CP, Elwood ET, Alexander DZ, Ritchie SC, Hendrix R, et al. (1996) Long-term acceptance of skin and cardiac allografts after blocking CD40 and CD28 pathways. Nature 381: 434-438.
24. Adams AB, Shirasugi N, Durham MM, Strobert E, Anderson D, et al. (2002) Calcineurin inhibitor-free CD28 blockade-based protocol protects allogeneic islets in nonhuman primates. Diabetes 51: 265-270.
25. Boden E, Tang Q, Bour-Jordan H, Bluestone JA (2003) The role of CD28 and CTLA4 in the function and homeostasis of CD4+CD25+ regulatory T cells. Novartis Found Symp 252: 55-63.
26. Tang Q, Smith M, Szot GL, Zhou P, Alegre ML, et al. (2003) CD28/B7 regulation of anti-CD3-mediated immunosuppression in vivo. J Immunol 170: 1510-1516.
27. Vincenti F, Kirk AD (2008) What’s next in the pipeline. Am J Transplant 8: 1972-1981.
28. Larsen CP, Pearson TC, Adams AB, Tso P, Shirasugi N, et al. (2005) Rational Development of LEA29Y (belatacept), a high-affinity variant of CTLA4-Ig with potent immunosuppressive properties. Am J Transplant 5: 443-453.
29. Balasa B, Kraft T, Patstone G, Lee J, Tisch R, et al. (1997) CD40 ligand-CD40 interactions are necessary for the initiation of insulins and diabetes in nonobese diabetic mice. J Immunol 159: 2670-2672.
30. Berney T, Pileggi A, Molano RD, Poggioli R, Zahr E, et al. (2003) The effect of simultaneous CD154 and LFA-1 blockade on the survival of allogeneic islet grafts in nonobese diabetic mice. Transplantation 76: 1669-1674.
31. Molano RD, Pileggi A, Berney T, Poggioli R, Zahr E, et al. (2003) Prolonged islet allograft survival in diabetic NOD mice by targeting CD45RB and CD154. Diabetes 52: 957-964.
32. Rossini AA, Mordes JP, Greiner DL, Stoff JS (2001) Islet cell transplantation tolerance. Transplantation 72: 543-546.
33. Adams AB, Shirasugi N, Jones TR, Durham MM, Strobert EA, et al. (2005) Development of a chimeric anti-CD40 monoclonal antibody that synergizes with LEA29Y to prolong islet allograft survival. J Immunol 174: 542-550.
34. Ford ML, Larsen CP (2009) Translating costimulation blockade to the clinic: lessons learned from three pathways. Immunol Rev 229: 294-306.
35. Kawai T, Andrews D, Colvin RB, Sachs DH, Cosimi AB (2000) Thromboembolic complications after treatment with monoclonal antibody against CD40 ligand. Nat Med 6: 1146.
36. Wells AD, Walsh MC, Bluestone JA, Turka LA (2001) Signaling through CD28 and CTLA-4 controls two distinct forms of T cell anergy. J Clin Invest 108: 895-903.
37. Bluestone JA, Tang Q, Sedwick CE (2008) T regulatory cells in autoimmune diabetes: past challenges, future prospects. J Clin Immunol 28: 677-684.
38. Shevach EM (2002) CD4+ CD25+ suppressor T cells: more questions than answers. Nat Rev Immunol 2: 389-400.

39. Liston A, Nutsch KM, Ferr AG, Lund JM, Rasmussen JP, et al. (2008) Differentiation of regulatory Foxp3+ T cells in the thymic cortex. Proc Natl Acad Sci U S A 105: 11903-11908.

40. Zheng Y, Rudensky AY (2007) Foxp3 in control of the regulatory T cell lineage. Nat Immunol 8: 457-462.

41. Lenschow DJ, Herold KC, Rhee L, Patel B, Koons A, et al. (1996) CD28/B7 regulation of Th1 and Th2 subsets in the development of autoimmune diabetes. Immunity 5: 285-293.

42. Tang Q, Henriksen KJ, Bi M, Finger EB, Szot G, et al. (2004) In vitro-expanded antigen-specific regulatory T cells suppress autoimmune diabetes. J Exp Med 199: 1455-1465.

43. Putnam AL, Brusko TM, Lee MR, Liu W, Szot GL, et al. (2009) Expansion of human regulatory T-cells from patients with type 1 diabetes. Diabetes 58: 652-662.

44. Hsieh CS, Zheng Y, Liang Y, Fontenot JD, Rudensky AY (2006) An intersection between the self-reactive regulatory and nonregulatory T cell receptor repertoires. Nat Immunol 7: 401-410.

45. Hsieh CS, Liang Y, Tyznik AJ, Self SG, Liggitt D, et al. (2004) Recognition of the peripheral self by naturally arising CD25+ CD4+ T cell receptors. Immunity 21: 267-277.

46. Rossini AA, Handler ES, Greiner DL, Mordes JP (1991) Insulin dependent diabetes mellitus hypothesis of autoimmunity. Autoimmunity 8: 221-235.