

CD4⁺CD25⁺ Immune Regulatory Cells Are Required for Induction of Tolerance to Alloantigen via Costimulatory Blockade

By Patricia A. Taylor,^{*} Randolph J. Noelle,[‡] and Bruce R. Blazar^{*}

From the ^{*}University of Minnesota Cancer Center and Department of Pediatrics, Division of Bone Marrow Transplantation, Minneapolis, Minnesota 55455; and the [‡]Department of Microbiology, Dartmouth Medical College, Hanover, New Hampshire 03756

Abstract

Immune regulatory CD4⁺CD25⁺ cells play a vital role in the induction and maintenance of self-tolerance and are essential for T cell homeostasis and the prevention of autoimmunity. Induction of tolerance to allogeneic donor grafts is a clinically desirable goal in bone marrow and solid organ transplantation. To determine whether CD4⁺CD25⁺ cells regulate T cell responses to alloantigen and are critical for tolerance induction, murine CD4⁺ T cells were tolerized to alloantigen via ex vivo CD40 ligand (CD40L)/CD40 or CD28/cytotoxic T lymphocyte-associated antigen 4/B7 blockade resulting in secondary mixed leukocyte reaction hyporesponsiveness and tolerance to alloantigen in vivo. CD4⁺CD25⁺ T cells were found to be potent regulators of alloresponses. Depletion of CD4⁺CD25⁺ T cells from the CD4⁺ responder population completely abrogated ex vivo tolerance induction to alloantigen as measured by intact responses to alloantigen restimulation in vitro and in vivo. Addback of CD4⁺CD25⁺ T cells to CD4⁺CD25⁻ cultures restored tolerance induction. These data are the first to indicate that CD4⁺CD25⁺ cells are essential for the induction of tolerance to alloantigen and have important implications for tolerance-inducing strategies targeted at T cell costimulatory pathways.

Key words: regulatory T cell • IL-2 receptor α chain (CD25) • tolerance • transplantation • in vivo animal models

Introduction

Immunoregulatory CD4⁺CD25⁺ cells play a vital role in the induction and maintenance of peripheral self-tolerance. These professional regulatory cells prevent the activation and proliferation of potentially autoreactive T cells that have escaped thymic deletion or recognize extrathymic antigens. Sakaguchi et al. (1) found that the transfer of CD4⁺CD25⁻ T cells into nude mice led to the development of organ-specific and systemic autoimmune disorders which could be prevented by the cotransfer of CD4⁺CD25⁺ T cells. Other studies demonstrated that transfer of CD4⁺CD25⁺ T cells prevented autoimmunity resulting from neonatal thymectomy and inhibited the effector function of autoantigen-specific T cell clones (2–4). CD25-deficient mice develop a profound peripheral lymphadenopathy associated with autoimmune disorders (5). Although these data indicate that CD4⁺CD25⁺ cells are es-

sential for self-tolerance, their role in tolerance to alloantigen has not been studied.

Productive T cell activation and proliferation require two signaling events. The first signal, antigen recognition, is the engagement of the TCR with the MHC-peptide ligand complex on the surface of the APCs. Costimulatory signals are required for the full activation of the intracellular signaling cascade, IL-2 production, T cell proliferation, and effector function (6). In vivo blockade of the CD28/cytotoxic T lymphocyte-associated antigen (CTLA)-4/B7 and CD40 ligand (CD40L)/CD40 costimulatory pathways has been shown to induce tolerance to allografts (7–11). We have reported previously that ex vivo blockade of the CD40L/CD40 pathway results in tolerance induction of murine CD4⁺ T cells to alloantigen (12, 13). Because of the central role of CD4⁺CD25⁺ cells in self-tolerance, we investigated the potential role of these professional suppressor cells in regulating T cell responses to alloantigen and in the induction of tolerance to alloantigen.

To determine whether CD4⁺CD25⁺ cells were required for tolerance induction to alloantigen, we used an in vitro

Address correspondence to Bruce R. Blazar, Department of Pediatrics, BMT Division, University of Minnesota Cancer Center, MMC 109, 420 SE Delaware St., Minneapolis, MN 55455. Phone: 612-626-2734; Fax: 612-624-3913; E-mail: blaza001@tc.umn.edu

culture in which CD4⁺ T cells or CD4⁺CD25⁻ T cells were incubated with alloantigen in the presence of anti-CD40L or anti-B7 mAbs. Our data indicate that CD4⁺CD25⁺ T cells (8–12% of CD4⁺ cells in most strains of mice) are essential to achieve tolerance induction by costimulatory blockade as measured by antigen rechallenge in vitro and by adoptive T cell transfer into antigen-bearing hosts. These studies reveal a fundamental role for CD4⁺CD25⁺ cells in ex vivo tolerance induction and suggest that CD4⁺CD25⁺ cells may be vital to tolerance induction to alloantigen in vivo.

Materials and Methods

Mice. B6.C-H2^{bm12}/KhEg (bm12) mice were purchased from The Jackson Laboratory. C57BL/6 (B6) mice were purchased from the National Institutes of Health. B6 and bm12 (both H2^b) mice differ at three amino acids due to mutations in the class II I^A region.

In Vitro Mixed Leukocyte Reaction Cultures. B6 lymph node cells were depleted of NK cells (hybridoma PK136, rat IgG2a) and CD8⁺ T cells (hybridoma 2.43, rat IgG2b) by incubation with mAb, followed by passage through a goat anti-mouse and goat anti-rat Ig-coated column (Cytovax). Purified cells were ≥94% CD4⁺ T cells. Cells, depleted of CD25⁺ cells by incubation with anti-CD25 mAb (hybridoma 3C7, rat IgG2b; BD Pharmingen) and sheep anti-rat Dynabeads (Dyna) were 99% CD4⁺CD25⁻. Purified CD4⁺CD25⁺ and CD4⁺CD25⁻ cells, obtained by incubating CD4⁺ cells with anti-CD25 PE (hybridoma PC61, rat IgG1; BD Pharmingen) and sorting into positive and negative fractions (>90 and 99% pure, respectively) (FACS Vantage™; Becton Dickinson), were combined at the indicated ratios. Splenic bm12 stimulators were prepared by incubation with anti-Thy-1.2 mAb (hybridoma 30H-12, rat IgG2b) and anti-NK1.1 mAb plus baby rabbit complement (Neffenegger). The phenotype of splenic stimulators was ~90% B cells, 1–3% T cells, and ~7% macrophages. Bulk cultures of responder CD4⁺ or CD4⁺CD25⁻ T cells mixed with irradiated (30 Gy) stimulators at a 1:1 ratio at a final concentration of 0.5 × 10⁶ cells per milliliter were plated in 24-well plates (Costar) in DMEM (Bio-Whittaker) supplemented with 10% fetal bovine serum (HyClone), 50 mM 2-Me (Sigma Aldrich), 10 mM Hepes buffer, 1 mM sodium pyruvate (Life Technologies), amino acids (1.5 mM L-glutamine, L-arginine, and L-asparagine; Sigma Aldrich), and antibiotics (100 U/ml penicillin and 100 mg/ml streptomycin; Sigma Aldrich). Anti-CD40L mAb (hybridoma MR1, hamster IgG) or a mixture of anti-B7.1 mAb (hybridoma 16-10A1, hamster IgG or 1G10, rat IgG) and anti-B7.2 mAb (hybridoma 2D10 or GL1, both rat IgG) was added to the mixed leukocyte reaction (MLR) at 50 μg/ml. To determine stability of anti-CD40L mAb in cultures, supernatants were obtained from MLR cultures after 2 and 5 d of incubation. Anti-CD40L mAb was detected at >80% of added concentration on both days by an anti-hamster IgG ELISA assay (data not shown). Anti-CD40L mAb was found to be functional as assessed by binding/blocking assays with a CD40L-transfected cell line (data not shown). MLR cultures were incubated at 37°C, 10% CO₂. On day 9, cells were washed, counted, and either plated with fresh stimulator cells in the absence of mAb or infused in vivo as described below. To monitor primary and secondary MLR proliferation, responder and stimulator cells were plated in replicates of six at numbers indicated in 96-well round-bottomed microtiter plates (Costar). Wells were

pulsed with tritiated thymidine (1 μCi/well; Amersham Life Science) on the indicated days for 20–24 h before harvesting and counted in the absence of scintillant amplification on a β-plate reader (Packard Instrument Co.).

Adoptive T Cell Transfer and GVHD Lethality. To determine whether T cells tolerized to alloantigen in vitro could mount a response to alloantigen in vivo, bm12 recipients were sublethally irradiated with 6.0 Gy (¹³⁷Cesium) total body irradiation 4 h before cell infusion. Control-cultured or mAb-cultured MLR cells (10⁵) were infused into antigen-bearing bm12 recipients via tail-vein injection. In a separate experiment, freshly purified, naive whole CD4⁺, CD4⁺CD25⁺, whole CD4⁺ and CD4⁺CD25⁻, or whole CD4⁺ and CD4⁺CD25⁺ cells were infused into bm12 recipients. Mice were monitored daily for GVHD lethality.

Flow Cytometric Analysis. To determine the expression of CD40L on CD4⁺CD25⁻ versus CD4⁺CD25⁺ cells, purified cell populations were incubated with allstimulators for 4 d in the presence of 1 μg/ml anti-CD40L biotin (BD Pharmingen). The addition of a biotin-labeled antibody has been shown to stabilize cell surface expression of CD40L (14). This concentration of antibody is insufficient to inhibit alloresponses (unpublished data). Cells

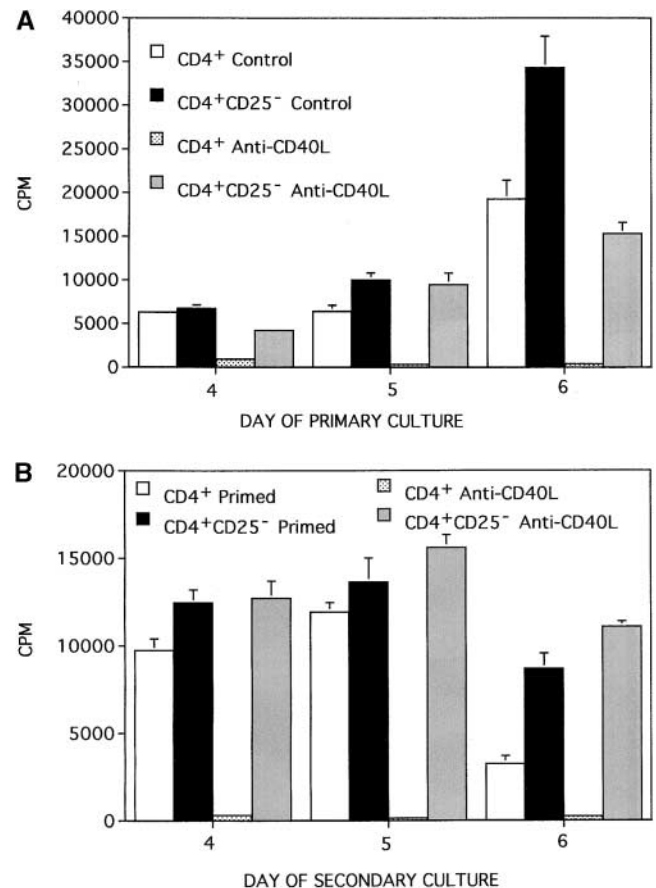


Figure 1. CD4⁺CD25⁺ T cells are required for tolerance induction by CD40L/CD40 costimulatory blockade. (A) Primary MLR culture consisted of 10⁵ cells per well whole CD4⁺ or CD4⁺CD25⁻ T cell responders and 10⁵ cells per well bm12 splenic stimulators and/or anti-CD40L mAb. (B) Secondary MLR culture consisted of 10⁴ cells per well responder cells from 9-d bulk cultures as described in (A) and 10⁵ cells per well fresh bm12 stimulators. Tritiated thymidine was added 20 h before harvesting. On the y-axis are mean cpm ± 1 SEM. On the x-axis are days in culture. One of five representative experiments is shown.

were incubated with anti-CD4 FITC and SA-perCP (BD Pharmingen) and the level of CD40L expression evaluated on CD4⁺ cells (FACScalibur™, CELLQuest™ software; Becton Dickinson).

Results and Discussion

CD4⁺CD25⁺ Cells Are Required for the Inhibition of Primary Proliferation by Anti-CD40L mAb. Although data indicate that CD4⁺CD25⁺ cells are essential for self-tolerance, their role in the induction of tolerance to alloantigen has not been studied. We have published previously that murine whole CD4⁺ T cells incubated with allostimulator cells in the presence of anti-CD40L mAb results in an inhibition of primary MLR, hyporesponsiveness in secondary MLR, and tolerance to alloantigen *in vivo* (12, 13). To determine whether CD4⁺CD25⁺ cells were required for the induction of tolerance to alloantigen via *ex vivo* blockade of the CD40L/CD40 costimulatory pathway, MLR cultures were established with purified whole B6 CD4⁺ cells or B6 CD4⁺CD25⁻ cells as responders and bm12 splenic allostimulators. As reported previously, the addition of anti-CD40L mAb inhibited peak proliferative responses in the whole CD4⁺ cell population by 98% (Fig. 1 A). In

contrast, peak responses in the CD25-depleted CD4⁺ population were inhibited by only 55% (Fig. 1 A). A threefold increase in the concentration of anti-CD40L mAb did not result in greater inhibition of primary MLR (data not shown). Moreover, the CD25-depleted CD4⁺ cells reproducibly had a higher and more sustained peak alloresponse than did whole CD4⁺ control cells (5/5 experiments, Fig. 1 A, and data not shown).

Depletion of CD4⁺CD25⁺ Cells Abrogated the Induction of Hyporesponsiveness to Antigen Rechallenge In Vitro and In Vivo. To determine whether hyporesponsiveness to antigen rechallenge achieved in anti-CD40L mAb-treated primary MLR cultures required CD4⁺CD25⁺ cells, day-9 MLR cultures were washed and plated with fresh bm12 splenic stimulators in the absence of antibody. Both the whole CD4⁺ and the CD25-depleted CD4⁺ control-primed cells responded vigorously to alloantigen restimulation (Fig. 1 B). As expected, anti-CD40L-tolerized whole CD4⁺ cells were profoundly hyporesponsive to alloantigen restimulation. In striking contrast, CD25-depleted CD4⁺ cells that had been cultured with anti-CD40L mAb had secondary proliferative responses identical to (*n* = 2 experiments) or in excess of (*n* = 3 experiments) the control-primed cells

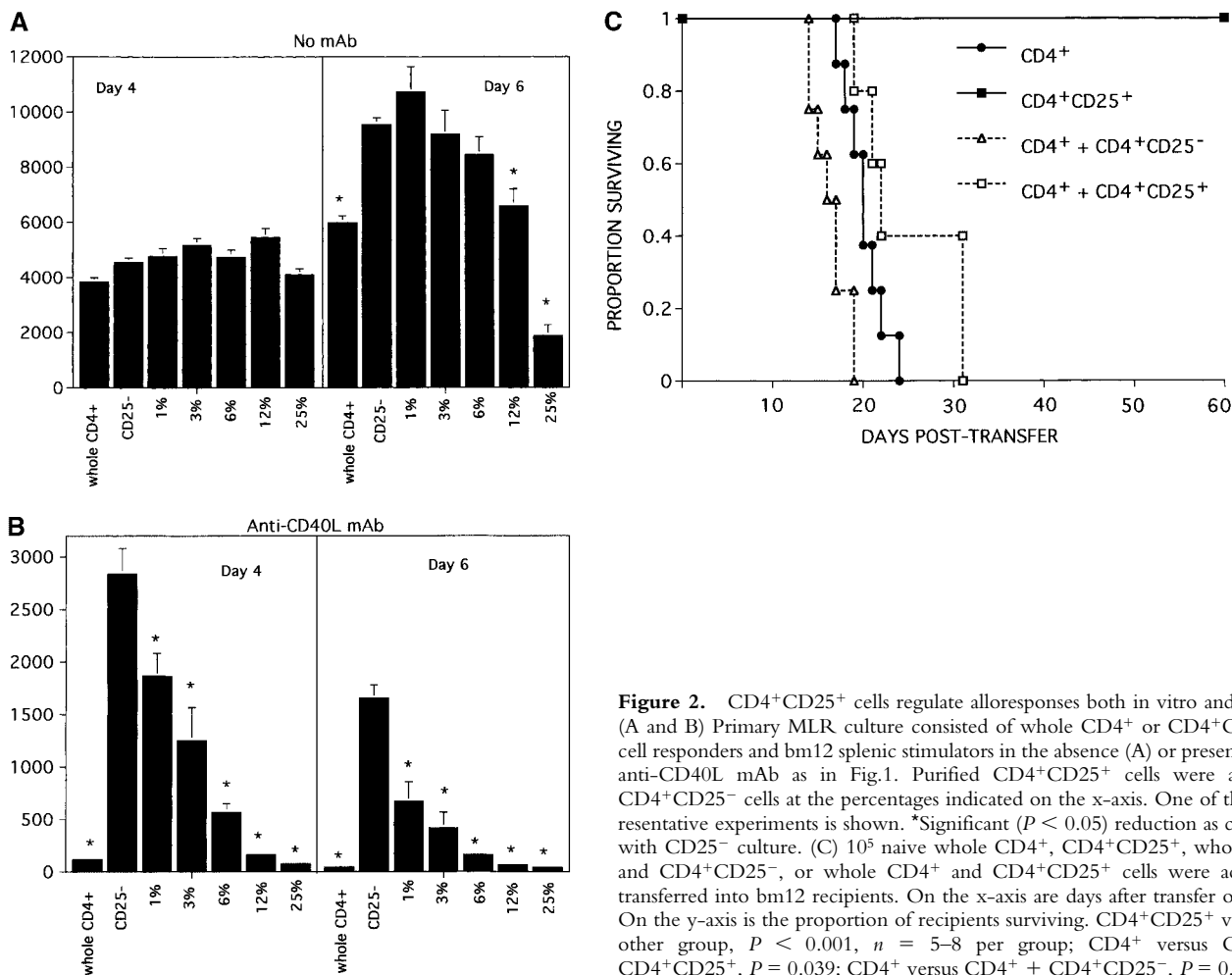


Figure 2. CD4⁺CD25⁺ cells regulate alloresponses both *in vitro* and *in vivo*. (A and B) Primary MLR culture consisted of whole CD4⁺ or CD4⁺CD25⁻ T cell responders and bm12 splenic stimulators in the absence (A) or presence (B) of anti-CD40L mAb as in Fig.1. Purified CD4⁺CD25⁺ cells were added to CD4⁺CD25⁻ cells at the percentages indicated on the x-axis. One of three representative experiments is shown. *Significant (*P* < 0.05) reduction as compared with CD25⁻ culture. (C) 10⁵ naive whole CD4⁺, CD4⁺CD25⁺, whole CD4⁺ and CD4⁺CD25⁻, or whole CD4⁺ and CD4⁺CD25⁺ cells were adoptively transferred into bm12 recipients. On the x-axis are days after transfer of T cells. On the y-axis is the proportion of recipients surviving. CD4⁺CD25⁺ versus any other group, *P* < 0.001, *n* = 5–8 per group; CD4⁺ versus CD4⁺ + CD4⁺CD25⁺, *P* = 0.039; CD4⁺ versus CD4⁺ + CD4⁺CD25⁻, *P* = 0.007.

(Fig. 1 B, and data not shown). These data indicate that CD4⁺CD25⁺ cells were essential for the tolerization of CD4⁺ T cells induced via ex vivo CD40L/CD40 blockade.

To further investigate the role of CD25⁺ cells on in vitro alloresponses, various numbers of purified CD4⁺CD25⁺ cells were added to CD4⁺CD25⁻ responder cells in both the absence and the presence of anti-CD40L mAb and proliferation was monitored (Fig. 2). Anti-CD40L mAb inhibited alloresponses of whole CD4⁺ cells (containing 12% CD4⁺CD25⁺ cells) by 97% on day 4 and 99% on day 6 of culture. In contrast, anti-CD40L mAb inhibited alloresponses of CD4⁺CD25⁻ cells by only 25% on day 4 and 72% on day 6 as compared with whole CD4⁺ cells (Fig. 2, A and B). The addition of CD4⁺CD25⁺ cells in the presence of anti-CD40L mAb resulted in increasingly profound inhibition of proliferation in a dose-dependent fashion (Fig. 2 B). The addition of as few as 1% CD4⁺CD25⁺ inhibited alloresponses of CD25⁻ cells in the presence of anti-CD40L mAb. Because the degree of inhibition of proliferation by CD4⁺CD25⁺ cells was more pronounced on day 6 than on day 4, these data suggest that CD4⁺CD25⁺ cells may become more potent regulatory cells with increased culture duration. On day 6, in the absence of antibody, the addition of 12% CD4⁺CD25⁺ cells prevented the hyperproliferative alloresponse of CD4⁺CD25⁻ cells. The addition of 25% CD4⁺CD25⁺ cells had a pronounced suppressive effect even in the absence of anti-CD40L mAb (Fig. 2 A). These data indicate that CD4⁺CD25⁺ cells are required for the maximal inhibition of primary responses to alloantigen by the addition of anti-CD40L mAb and that CD4⁺CD25⁺ cells have a potent capacity to regulate CD4⁺ T cell alloresponses.

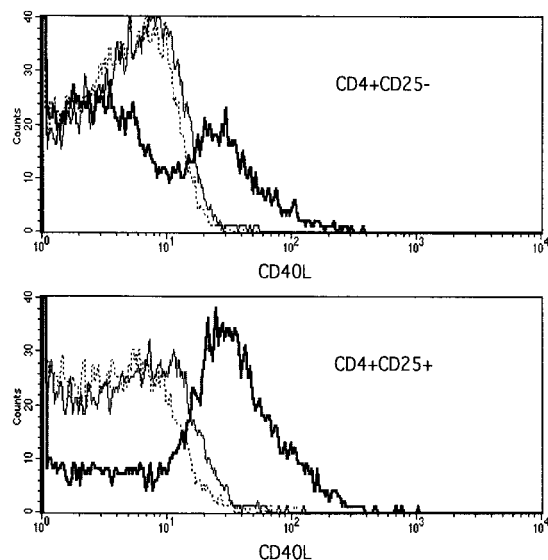


Figure 3. CD4⁺CD25⁺ cells upregulate CD40L on their cell surface during incubation with allostimulators. CD4⁺CD25⁻ (top) and CD4⁺CD25⁺ (bottom) cells were phenotyped for constitutive and inducible expression of CD40L. Dotted line indicates negative control. The thin solid line indicates the constitutive expression of freshly purified naive cells. The bold line indicates CD40L expression after 4-d incubation with allostimulators.

The adoptive transfer of alloreactive T cells results in GVHD lethality, a clinically relevant in vivo model of allo-responsiveness (12, 13). To investigate the role of CD4⁺CD25⁺ cells on alloresponses in vivo, 10⁵ freshly isolated, naive whole CD4⁺, CD4⁺CD25⁺, whole CD4⁺ and CD4⁺CD25⁻, or whole CD4⁺ and CD4⁺CD25⁺ cells were infused into bm12 recipients (Fig. 2 C). CD4⁺CD25⁺ cells did not mediate GVHD lethality in any recipients in contrast to the uniform lethality mediated by naive whole CD4⁺ cells 23 d after transfer. Mortality was delayed by 8 d in mice receiving equal numbers of purified CD4⁺CD25⁺ cells and whole CD4⁺ cells as compared with mice receiving only whole CD4⁺ cells ($P = 0.039$). In contrast, the coinjection of CD4⁺CD25⁻ cells with whole CD4⁺ cells accelerated GVHD mortality by 1 wk as compared with recipients receiving only whole CD4⁺ cells ($P = 0.007$). These data provide further evidence that naive CD4⁺CD25⁺ T cells have a modest capacity to downregulate alloreactive T cells in vivo.

To determine whether CD40L was expressed on CD4⁺CD25⁺ cells, we examined cell surface expression of

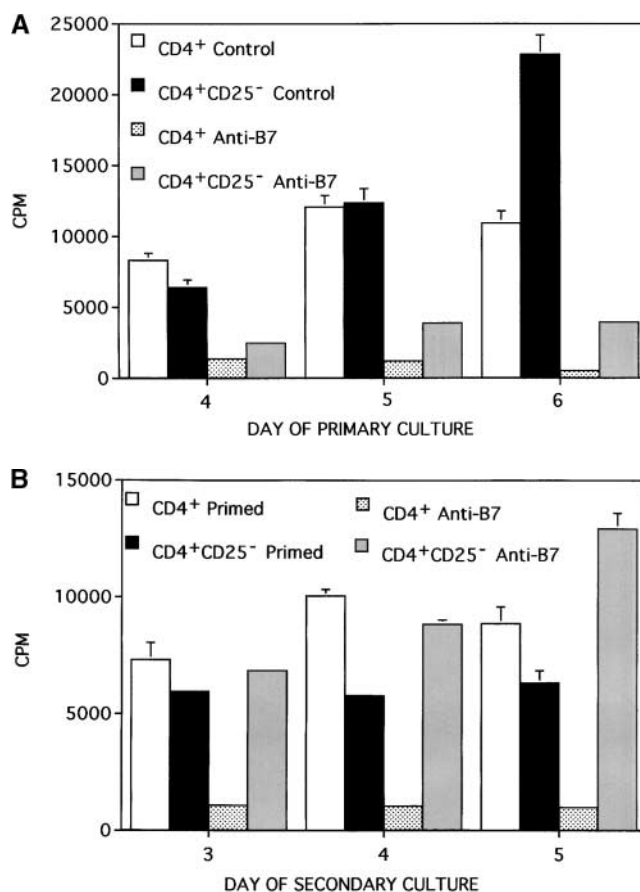


Figure 4. CD4⁺CD25⁺ T cells are required for tolerance induction by CD28/CTLA-4/B7 costimulatory blockade. (A) Primary MLR culture consisted of whole CD4⁺ or CD4⁺CD25⁻ T cell responders and bm12 splenic stimulators and/or anti-B7 mAbs as in Fig. 1. (B) Secondary MLR culture consisted of 10⁴ cells per well responder cells from 9-d bulk cultures as described in (A) and fresh bm12 stimulators. One of four representative experiments is shown.

CD40L on fresh, naive CD4⁺CD25⁺ cells and CD4⁺CD25⁻ cells (Fig. 3). Although there was only a very modest increase in constitutive expression of CD40L on CD25⁺ cells as compared with CD25⁻ cells, by day 4 of culture with allostimulators 69% of purified CD4⁺CD25⁺ cells expressed CD40L. In contrast, a lower proportion (30%) of CD4⁺CD25⁻ cells expressed CD40L. These data demonstrate that CD40L is expressed on a high proportion of CD4⁺CD25⁺ cells after alloantigen stimulation and suggest that the CD40L/CD40 pathway may play an important role in the regulation of alloresponses in CD4⁺CD25⁺ cells.

To determine if the requirement of CD4⁺CD25⁺ T cells for tolerance induction was unique to blockade of the CD40L/CD40 costimulatory pathway, experiments were performed using anti-B7.1 and anti-B7.2 mAbs to block the CD28/CTLA-4/B7 pathway. Although inhibition of primary MLR of CD4⁺CD25⁻ cells was more profound with anti-B7 mAbs than with anti-CD40L mAb (compare Figs. 4 A with 1 A), the degree of inhibition was not nearly as profound as that achieved with whole CD4⁺ cells. More importantly, CD4⁺CD25⁻ cells that had been cultured with anti-B7 mAbs had intact or increased proliferative responses upon restimulation with alloantigen (Fig. 4 B). These data indicate that CD4⁺CD25⁺ cells are required for the ex vivo induction of tolerance to alloantigen via costimulatory blockade of either the CD40L/CD40 or the CD28/CTLA-4/B7 pathway.

An advantage of our ex vivo tolerization model is that it allows a clinically relevant, in vivo readout of alloresponsiveness. To assess alloreactivity in vivo, aliquots of cells used to establish secondary MLRs were adoptively transferred into bm12 recipients. All recipients of either whole CD4⁺ or CD4⁺CD25⁻ control-primed cells died of GVHD 20–25 d after transfer (Fig. 5 A). Whole CD4⁺ cells tolerized to alloantigen by a 9-d incubation in the presence of anti-CD40L mAb did not mediate GVHD lethality providing definitive in vivo evidence that tolerance induction had been successful. In contrast, all recipients of anti-CD40L mAb-cultured CD4⁺CD25⁻ T cells died of GVHD 18 d after transfer (Fig. 5 A). Similar results were seen with cultures incubated with anti-B7 mAbs (Fig. 5 B). No recipients of anti-B7-tolerized whole CD4⁺ cells died of GVHD. In contrast, all recipients of anti-B7-cultured CD25-depleted CD4⁺ cells died of GVHD by 25 d. These data indicate an essential requirement for CD4⁺CD25⁺ cells for tolerance induction as measured by protection from GVHD lethality.

Collectively, our data indicate that CD4⁺CD25⁺ cells are required for the ex vivo induction of tolerance to alloantigen via costimulatory blockade and that CD4⁺CD25⁺ cells regulate responses to alloantigen. Previous studies have described CD4⁺CD25⁺ cells as important immunoregulatory cells essential for T cell homeostasis and for the prevention of autoimmunity. Mice deficient in this population have a high incidence of various autoimmune disorders (1–4, 15, 16). CD4⁺CD25⁺ cells have been shown to suppress diseases induced by autoantigen-specific T cell clones (17). Shimizu et al. (18) found that depletion

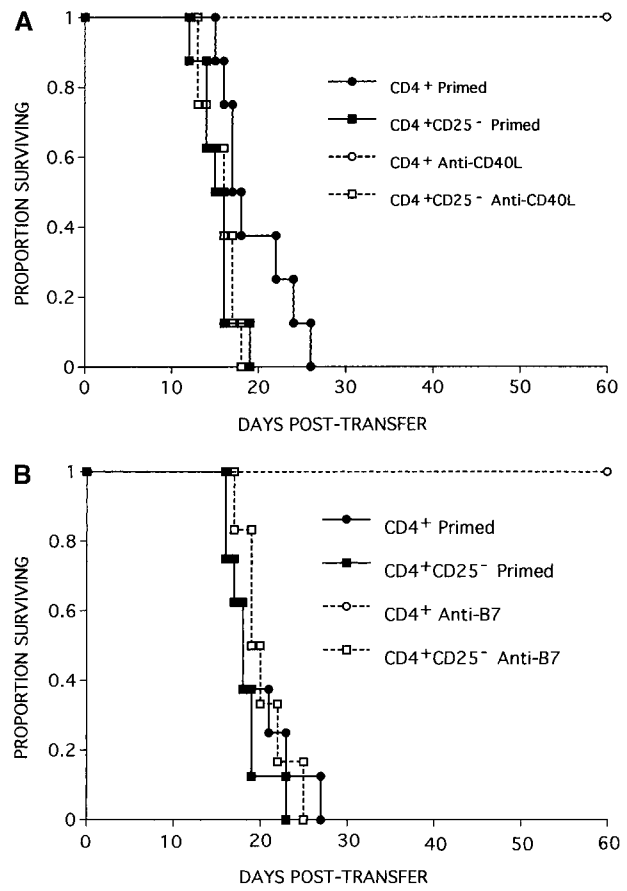


Figure 5. Depletion of CD4⁺CD25⁺ cells abrogated protection from GVHD lethality induced by tolerization via costimulatory blockade. 10⁵ cells from washed, 9-d bulk primary MLR cultures as described in Figs. 1 and 4 were injected into bm12 recipients. (A) Anti-CD40L-tolerization. Two replicate experiments with similar results were pooled; *n* = 16. CD4⁺ Anti-CD40L versus any other group, *P* < 0.001; CD4⁺ Primed versus CD4⁺CD25⁻ Primed, *P* = 0.056. (B) Anti-B7-tolerization. *n* = 8 per group. CD4⁺ Anti-B7 versus any other group, *P* < 0.001.

of CD4⁺CD25⁺ cells resulted in the breaking of immunological tolerance to autologous tumors and evoked tumor immunity. These studies have implicated CD4⁺CD25⁺ cells as an active mechanism for the induction and maintenance of immunologic tolerance to self. Fewer studies have addressed the role CD4⁺CD25⁺ T cells may play in response to nonself antigen. Sakaguchi et al. (1) found that nude mice rejected allogeneic skin grafts faster if transferred lymphocytes were first depleted of CD25⁺ cells suggesting that these immunoregulatory cells downregulate responses to alloantigen. This is consistent with our finding that CD25-depleted CD4⁺ cells had a heightened proliferative response to alloantigen and that the addition of CD4⁺CD25⁺ cells to either whole CD4⁺ cells or CD25-depleted CD4⁺ cells had a suppressive effect on in vitro and in vivo alloresponses. It is necessary to note that our culture system involves direct recognition to a single MHC class II disparity and therefore, may not be fully extrapolatable to other allogeneic systems. Nonetheless, our data extend the field by demonstrating an essential requirement of

the CD4⁺CD25⁺ regulatory population in allotolerance induced by costimulatory blockade. We hypothesize that these data implicating a professional suppressor cell population in the regulation of immune responses to nonself antigens may have important ramifications in many areas of clinical immunology.

The mechanism for the requirement of CD4⁺CD25⁺ cells in tolerance induction remains to be elucidated. Studies are in progress to determine whether CD4⁺CD25⁺ cells are the direct targets in costimulatory blockade tolerization strategies or if CD4⁺CD25⁺ cells provide indirect but essential help for tolerization of CD4⁺CD25⁻ cells. Thornton and Shevach (19, 20) have shown that CD4⁺CD25⁺ T cells block the induction of IL-2 production by the CD4⁺CD25⁻ cells at the level of RNA transcription and that activation enhances the immunosuppressive function of these cells. Activated CD4⁺CD25⁺ cells induced to become potent inhibitors of IL-2 transcription could facilitate anergy induction. Consistent with this hypothesis, IL-2 production is reduced by >90% in primary and secondary cultures of tolerized cells (13). Moreover, the addition of exogenous IL-2 precludes anergy induction in anti-CD40L, mAb-treated primary culture (12). Our data indicate that the activation of CD4⁺CD25⁺ cells is important in tolerance induction. The suppressive effect of the addition of 25% CD4⁺CD25⁺ cells to CD4⁺CD25⁻ cultures, not evident on day 4, was profound on day 6 of culture. Interestingly, we have found that a 4-d ex vivo incubation with anti-CD40L mAb was insufficient to induce tolerance in whole CD4⁺ cells (13) suggesting a link between the activation of CD4⁺CD25⁺ cells and tolerance induction. Takahashi et al. (21) offers the intriguing suggestion that CTLA-4 and CD28 may have unique roles in CD4⁺CD25⁺ cells with costimulation through CTLA-4 or CD28 resulting in the activation or attenuation, respectively, of suppressor function (21).

However, these findings do not address the more provocative issue of why CD4⁺CD25⁻ cells are resistant to tolerance induction via ex vivo costimulatory blockade. One potential explanation may relate to the mechanisms by which CD4⁺CD25⁺ cells influence CD4⁺CD25⁻ cells. It has been reported recently that CTLA-4, the inhibitory T cell receptor for B7 molecules, is constitutively expressed on CD25⁺CD4⁺ regulatory cells but not CD4⁺CD25⁻ cells (21, 22). Since CTLA-4/B7 engagement has been reported to be required for the induction of peripheral T cell tolerance in vivo (23), constitutive CTLA-4 on CD4⁺CD25⁺ cells may facilitate ex vivo tolerance induction. CTLA-4/B7 engagement also has been shown to result in the secretion of the immunosuppressive cytokine, TGF- β , by CD4⁺CD25⁺ cells (22) which might facilitate tolerance induction. Although other studies have indicated that cell-cell contact appears to be required for the downregulatory capacity of CD4⁺CD25⁺ cells, it is possible that unidentified, labile, soluble factor(s) may be involved (15, 19, 20, 24). However, we have shown that exogenously added TGF- β alone (1 ng/ml) did not induce tolerance in our model (25) and further, that reduced alloreactivity is not

achieved in our model via a Th2 skewing or by the production of the immunoregulatory cytokine, IL-10 (13).

Antibodies blocking costimulation administered in vivo can induce tolerance to donor bone marrow and organ allografts (7, 26–28). It is unknown whether depletion of host CD4⁺CD25⁺ cells would preclude tolerance to donor allografts, but it is tempting to speculate that they may also be essential for in vivo tolerance induction to alloantigen, at least in a strategy involving costimulatory blockade. Future studies will address this question. Although a CD4⁺CD25⁺ T cell with suppressor function has not been published in humans, there is evidence that professional immune regulatory/suppressor cells with similar function, if not phenotype, exist in humans and mice. A conditioning regime for allotransplant that preserves these cells may be clinically desirable.

The authors would like to thank Ms. Brigit G. Durell for excellent technical assistance and Dr. Laurence Turka for helpful discussions and suggestions.

This work was supported by National Institutes of Health grants R01 AI34495, 2R37 HL56067, R01 HL63452, and P01 AI35225, and a grant from the National Marrow Donor Program (to B.R. Blazar).

Submitted: 30 November 2000

Revised: 9 March 2001

Accepted: 20 March 2001

References

1. Sakaguchi, S., N. Sakaguchi, M. Asano, M. Itoh, and M. Toda. 1995. Immunologic self-tolerance maintained by activated T cells expressing IL-2 receptor α -chains (CD25). Breakdown of a single mechanism of self-tolerance causes various autoimmune diseases. *J. Immunol.* 155:1151–1164.
2. Suri-Payer, E., P.J. Kehn, A.W. Cheever, and E.M. Shevach. 1996. Pathogenesis of post-thymectomy autoimmune gastritis. Identification of anti-H/K adenosine triphosphatase-reactive T cells. *J. Immunol.* 157:1799–1805.
3. Asano, M., M. Toda, N. Sakaguchi, and S. Sakaguchi. 1996. Autoimmune disease as a consequence of developmental abnormality of a T cell subpopulation. *J. Exp. Med.* 184:387–396.
4. Bonomo, A., P.J. Kehn, E. Payer, L. Rizzo, A.W. Cheever, and E.M. Shevach. 1995. Pathogenesis of post-thymectomy autoimmunity. Role of syngeneic MLR-reactive T cells. *J. Immunol.* 154:6602–6611.
5. Willerford, D.M., J. Chen, J.A. Ferry, L. Davidson, A. Ma, and F.W. Alt. 1995. Interleukin-2 receptor alpha chain regulates the size and content of the peripheral lymphoid compartment. *Immunity.* 3:521–530.
6. Schwartz, R.H. 1990. A cell culture model for T lymphocyte clonal anergy. *Science.* 248:1349–1356.
7. Blazar, B.R., P.A. Taylor, A. Panoskaltis-Mortari, J. Buhlman, J. Xu, R.A. Flavell, R. Korngold, R. Noelle, and D.A. Vallera. 1997. Blockade of CD40 ligand-CD40 interaction impairs CD4⁺ T cell-mediated alloreactivity by inhibiting mature donor T cell expansion and function after bone marrow transplantation. *J. Immunol.* 158:29–39.
8. Seung, E., N. Iwakoshi, B.A. Woda, T.G. Markees, J.P. Mordes, A.A. Rossini, and D.L. Greiner. 2000. Allogeneic

- hematopoietic chimerism in mice treated with sublethal myeloablation and anti-CD154 antibody: absence of graft-versus-host disease, induction of skin allograft tolerance, and prevention of recurrent autoimmunity in islet-allografted NOD/Lt mice. *Blood*. 5:2175–2182.
9. Durham, M.M., A.W. Bingaman, A.B. Adams, J. Ha, S.Y. Waitze, T.C. Pearson, and C.P. Larsen. 2000. Cutting edge: administration of anti-CD40 ligand and donor bone marrow leads to hemopoietic chimerism and donor-specific tolerance without cytoreductive conditioning. *J. Immunol.* 165:1–4.
 10. Kirk, A.D., L.C. Burkly, D.S. Batty, R.E. Baumgartner, J.D. Berning, K. Buchanan, J.H. Fechner, Jr., R.L. Germond, R.L. Kampen, N.B. Patterson, et al. 1999. Treatment with humanized monoclonal antibody against CD154 prevents acute renal allograft rejection in nonhuman primates. *Nat. Med.* 5:686–693.
 11. Parker, D.C., D.L. Greiner, N.E. Phillips, M.C. Appel, A.W. Steele, F.H. Durie, R.J. Noelle, J.P. Mordes, and A.A. Rossini. 1995. Survival of mouse pancreatic islet allografts in recipients treated with allogeneic small lymphocytes and antibody to CD40 ligand. *Proc. Natl. Acad. Sci. USA.* 92:9560–9564.
 12. Blazar, B.R., P.A. Taylor, R.J. Noelle, and D.A. Vallera. 1998. CD4⁺ T cells tolerized ex vivo to host alloantigen by anti-CD40 ligand (CD40L:CD154) antibody lose their graft-versus-host disease lethality capacity but retain nominal antigen responses. *J. Clin. Invest.* 102:473–482.
 13. Taylor, P.A., A. Panoskaltis-Mortari, R.J. Noelle, and B.R. Blazar. 2000. Analysis of the requirements for the induction of CD4⁺ T cell alloantigen hyporesponsiveness by ex vivo anti-CD40 ligand antibody. *J. Immunol.* 164:612–622.
 14. Roy, M., A. Aruffo, J. Ledbetter, P. Linsley, M. Kehry, and R. Noelle. 1995. Studies on the interdependence of gp39 and B7 expression and function during antigen-specific immune responses. *Eur. J. Immunol.* 25:596–603.
 15. Takahashi, T., Y. Kuniyasu, M. Toda, N. Sakaguchi, M. Itoh, M. Iwata, J. Shimizu, and S. Sakaguchi. 1998. Immunologic self-tolerance maintained by CD25⁺CD4⁺ naturally anergic and suppressive T cells: induction of autoimmune disease by breaking their anergic/suppressive state. *Int. Immunol.* 10:1969–1980.
 16. Shevach, E.M. 2000. Regulatory T cells in autoimmunity. *Annu. Rev. Immunol.* 18:423–449.
 17. Suri-Payer, E., A.Z. Amar, A.M. Thornton, and E.M. Shevach. 1998. CD4⁺CD25⁺ T cells inhibit both the induction and effector function of autoreactive T cells and represent a unique lineage of immunoregulatory cells. *J. Immunol.* 160:1212–1218.
 18. Shimizu, J., S. Yamazaki, and S. Sakaguchi. 1999. Induction of tumor immunity by removing CD25⁺CD4⁺ T cells: a common basis between tumor immunity and autoimmunity. *J. Immunol.* 163:5211–5218.
 19. Thornton, A.M., and E.M. Shevach. 1998. CD4⁺CD25⁺ immunoregulatory T cells suppress polyclonal T cell activation in vitro by inhibiting interleukin 2 production. *J. Exp. Med.* 188:287–296.
 20. Thornton, A.M., and E.M. Shevach. 2000. Suppressor effector function of CD4⁺CD25⁺ immunoregulatory T cells is antigen nonspecific. *J. Immunol.* 164:183–190.
 21. Takahashi, T., T. Tagami, S. Yamazaki, T. Uede, J. Shimizu, N. Sakaguchi, T.W. Mak, and S. Sakaguchi. 2000. Immunologic self-tolerance maintained by CD25⁺CD4⁺ regulatory T cells constitutively expressing cytotoxic T lymphocyte-associated antigen 4. *J. Exp. Med.* 192:303–310.
 22. Read, S., V. Malmstrom, and F. Powrie. 2000. Cytotoxic T lymphocyte-associated antigen 4 plays an essential role in the function of CD25⁺CD4⁺ regulatory cells that control intestinal inflammation. *J. Exp. Med.* 192:295–302.
 23. Perez, V.L., L. Van Parijs, A. Biuckians, X.X. Zheng, T.B. Strom, and A.K. Abbas. 1997. Induction of peripheral T cell tolerance in vivo requires CTLA-4 engagement. *Immunity.* 6:411–417.
 24. Cederbom, L., H. Hall, and F. Ivars. 2000. CD4⁺CD25⁺ regulatory T cells down-regulate co-stimulatory molecules on antigen-presenting cells. *Eur. J. Immunol.* 30:1538–1543.
 25. Zeller, J.C., A. Panoskaltis-Mortari, W.J. Murphy, F.W. Ruscetti, S. Narula, M.G. Roncarolo, and B.R. Blazar. 1999. Induction of CD4⁺ T cell alloantigen-specific hyporesponsiveness by IL-10 and TGF-β. *J. Immunol.* 163:3684–3691.
 26. Wekerle, T., J. Kurtz, H. Ito, J.V. Ronquillo, V. Dong, G. Zhao, J. Shaffer, M.H. Sayegh, and M. Sykes. 2000. Allogeneic bone marrow transplantation with co-stimulatory blockade induces macrochimerism and tolerance without cytoreductive host treatment. *Nat. Med.* 6:464–469.
 27. Zheng, X.X., M.H. Sayegh, X.G. Zheng, Y. Li, P.S. Linsley, R. Peach, F. Borriello, T.B. Strom, A.H. Sharpe, and L.A. Turka. 1997. The role of donor and recipient B7-1 (CD80) in allograft rejection. *J. Immunol.* 159:1169–1173.
 28. Kirk, A.D., D.M. Harlan, N.N. Armstrong, T.A. Davis, Y. Dong, G.S. Gray, X. Hong, D. Thomas, J.H. Fechner, Jr., and S.J. Knechtle. 1997. CTLA4-Ig and anti-CD40 ligand prevent renal allograft rejection in primates. *Proc. Natl. Acad. Sci. USA.* 94:8789–8794.