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The Link between the PDL1 Costimulatory Pathway and Th17 in Fetomaternal Tolerance

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Fetomaternal tolerance has been shown to depend both on regulatory T cells (Tregs) and negative signals from the PD1–PDL1 costimulatory pathway. More recently, IL-17–producing T cells (Th17) have been recognized as a barrier in inducing tolerance in transplantation. In this study, we investigate the mechanisms of PDL1-mediated regulation of fetomaternal tolerance using an alloantigen-specific CD4+ TCR transgenic mouse model system (ABM-tg mouse). PDL1 blockade led to an increase in embryo resorption and a reduction in litter size. This was associated with a decrease in Tregs, leading to a lower Treg/effector T cell ratio. Moreover, PDL1 blockade inhibited Ag-specific alloreactive T cell apoptosis and induced apoptosis of Tregs and a shift toward higher frequency of Th17 cells, breaking fetomaternal tolerance. These Th17 cells arose predominantly from CD4+Foxp3− cells, rather than from conversion of Tregs. Locally in the placenta, similar decrease in regulatory and apoptotic markers was observed by real-time PCR. Neutralization of IL-17 abrogated the anti-PDL1 effect on fetal survival rate and restored Treg numbers. Finally, the adaptive transfer of Tregs was also able to improve fetal survival in the setting of PDL1 blockade. This is to our knowledge the first report using an alloantigen-specific model that establishes a link between PDL1, Th17 cells, and fetomaternal tolerance.


A cceptance of the semiallogeneic fetus by the mother during pregnancy represents a physiologic model of in vivo immune tolerance (1, 2). Several mechanisms have been reported to take part in this complex interplay. More recently, the importance of regulation and trafficking of regulatory T cells at the fetomaternal interface has been investigated, even though its mechanisms remain a matter of debate (3). Because tolerance has been reconsidered as a balance rather than an all-or-none phenomenon (4), a number of studies both in transplantation and in fetomaternal mouse models are focusing on the role of regulatory T cells (Tregs), effector T cells (Teff), and costimulatory pathways and their reciprocal influence in balancing the immune response (5–7).

The PD1–PDL1 negative costimulatory pathway has been demonstrated to be critical for peripheral transplantation tolerance due to its ability to alter the balance between pathogenic T cells and Tregs (8, 9). Expression of PDL1 in donor tissue was crucial for the prevention of chronic rejection in a heart transplant model (10) and for the maintenance of tolerance at the uteroplacental interface (11). In a bone marrow transplantation model, both in vivo and in vitro, PD1–PDL1 costimulation blockade resulted in an increased lethality of graft-versus-host disease by increasing donor IFN-γ production and enhancing T cell alloimmune responses (12). In a diabetes model, PDL1 expression on the surface of islets provided protection against immunopathological injury after transplantation (13).

Our group has previously shown that the PD1–PDL1 negative costimulatory pathway plays a key role in inducing and maintaining fetomaternal tolerance in a mouse model. In particular, it was shown by Habicht et al. (14) that the expression of PDL1 on the surface of Tregs is essential to exert their suppressive effect and to control the maternal immune response. In fact, blocking PDL1 resulted in a loss of regulatory function and reduction in fetal survival rate. It has also been suggested that a deficiency of PDL1, in and of itself, may influence Teff and drive the balance toward fetal rejection by favoring Th1 and Th17 cell development and expansion (14). Consistent with that, several authors have reported the failure of the Th1/Th2 paradigm in fully explaining fetal rejection in different murine models (15–17) and allograft rejection in transplantation (18). It has also been recently observed that Th17 expansion is critical to initiate an alloimmune response, particularly in a Th1-deficient environment. Although no data are available in the allogeneic pregnancy model, Th17 expansion represents a barrier to establish tolerance (19, 20).

The aim of the current study was to investigate the mechanisms by which PDL1 mediates the interaction between Tregs and Teff and thereby directly affects the Th1/Th2/Th17 balance, leading to regulation at the fetomaternal interface. For this purpose, we took advantage of an alloantigen-specific CD4+ TCR transgenic mouse model system (ABM-tg mouse) to track alloantigen-specific cells generated during the immune response in a single class II mismatch murine model of fetomaternal tolerance.
Materials and Methods

Mice

B6.PL-Thy1.2/CyJ (Thy1.1 B6) and B6.C-H-2^{Bm12}KsEg (Bm12) mice were purchased from The Jackson Laboratory. ABM (anti-Bm12) mice were generated as previously reported (21) and maintained as a breeding colony in our animal facility. Foxp3 knock-in (Foxp3-GFP) mice were a kind gift of Dr. Rudensky (University of Washington). ABM Tg.Foxp3-GFP mice on B6 background were generated by crossing ABM mice with Foxp3 knock-in mice for eight generations in our own facility. All mice were housed in accordance with institutional and National Institutes of Health guidelines.

Treatment protocol

Pregnant female Thy1.1 B6 mice were injected i.p. with the blocking anti-Bm12 Ab. All mice colony in our animal facility. Foxp3 knock-in (Foxp3-GFP) mice were purchased from The Jackson Laboratory. ABM (anti-Bm12) mice have recently been described (20) and was administered i.p. at a dose of 84 μg on 4.5, 5.5, 6.5, 7.5, 8.5, and 11 days postcoitus (dpc).

Timed matings and resorption rates

Females were inspected daily for vaginal plugs, and sighting of a vaginal plug was designated as day 0.5 of pregnancy. Plugged females were either sacrificed between 11.5 and 13.5 dpc to examine the number of implantations and resorbing sites or were monitored until parturition and the number of pups born recorded.

Adoptive transfer of TCR-tg T cells

Adoptive transfer of ABM TCR-tg T cells was performed as previously described (21). Briefly, spleens and lymph nodes were harvested from naive ABM TCR-tg mice, and pooled single-cell leukocyte suspensions were prepared. CD4+ T cells were purified by magnetic bead negative selection (Miltenyi Biotec, Auburn, CA) with >90% purity. Typically, >90% of CD4+ T cells expressed the transgenic (tg) TCR as determined by anti-TCR Vβ1.2 and anti-TCR Vβ8.1 Ab staining. ABM TCR-tg naive CD4+ T cells (3 × 10^6) were then injected i.p. into Thy 1.1 B6 females mated with Bm12 males (day 0). On day 1 and day 2 after transfer of cells, a few mice were sacrificed, spleen and lymph nodes were taken, and cells were counted to determine if similar numbers were present to begin with in the mice designated to the anti-PDL1 treatment group versus control group. Other mice received anti-PDL1 mAb or control IgG on 11.5–13.5 dpc, lymph nodes and spleens were collected, and single-cell leukocyte suspensions were prepared. ABM TCR-tg T cells were identified by staining for CD90 1.2 (Thy1.2) surface marker at flow cytometry. Placenta samples were collected as well for real-time PCR (RT-PCR) and intracellular cytokine staining by flow cytometry. Adoptive transferred cells used were naive Thy 1.2 ABM TCR-tg (Vα8.1/Vβ2.1) CD4+ T cells.

Adoptive transfer of Thy1.2+Foxp3-GFP TCR-tg T cells

Adoptive transfer of Thy1.2+Foxp3-GFP TCR-tg T cells was performed as previously described in the ABM TCR-tg system (21). Briefly, spleens and lymph nodes were harvested from ABM Tg.Foxp3-GFP mice, and pooled single-cell leukocyte suspensions were prepared. CD4+ T cells were purified by magnetic bead positive selection (Miltenyi) with >90% purity. ABM Tg.Foxp3-GFP CD4+ T cells express CD90.2 (Thy 1.2) on their surfaces. More than 90% of CD4+ T cells expressed the tg TCR, and ~2% of CD4+ T cells were GFP+. CD4+ isolated cells were then flow-sorted for Foxp3-GFP+ and GFP– cells with >98% purity. Subsequently, 0.3 × 10^6 Thy1.2+Foxp3-GFP+ cells were injected i.p. into Thy 1.1 B6 females mated with Bm12 males (day 0) as described previously. As a control, adoptive transfer of 0.3 × 10^6 Thy1.2+Foxp3-GFP+ cells into Thy 1.1 B6 females mated with Bm12 males (day 0) was also performed.

To evaluate the fate of these transferred cells, we harvested lymphoid organs on day 3 after cell injection in pregnant females, in the setting of administration of either IgG or anti-PDL1 Ab. Part of the collected cells were then stained for Thy 1.2 and Foxp3, and part was cultured with irradiated Bm12 splenocytes for 48 h, followed by measurement of IL-17 production by Lumimex as detailed later. To evaluate the effect of Ag-specific Treg transfer on litter size, a group of pregnant females treated with either IgG or anti-PDL1 was followed long-term.

Flow cytometry

Cells (1 × 10^6) were stained with biotinylated Thy1.2 (CD90.2) followed by allophycocyanin- or PerCP-conjugated streptavidin to identify the adoptively transferred cells. Teff were determined by staining with anti-CD4 PerCP, anti-CD8 FITC, anti-CD62L, allophycocyanin, and anti-CD44 PE (all from BD Pharmingen) and analyzed for cells bearing the CD44hiCD62Llow phenotype. Tregs were detected by staining with anti-CD4 FITC, anti-CD25 PE, and intracellular staining with Foxp3 allophycocyanin (eBioscience) as per the manufacturer’s instructions. In addition, Thy1.2+Tregs were also stained with PE-conjugated PDL1 (MH5 clone from BD Pharmingen). Apoptosis was evaluated by annexin V and 7-aminoactinomycin D staining. Four-color flow cytometry was performed on a FACSCalibur (Becton Dickinson, San Jose, CA), and cells were analyzed using FlowJo software.

ELISPOT assay

Splenocytes from pregnant mice (female Thy1.1 B6 mated with Bm12 male) were obtained as single-cell suspensions and used as responder cells (5 × 10^6). Splenocytes from male Bm12 mice were irradiated and used as stimulator cells. The ELISPOT assay was adapted to detect IFN-γ, IL-4, and IL-17–secreting cells as described previously (14).

Luminex cytokines assay

For cytokine analysis, splenocytes harvested at 11.5 and 13.5 dpc from pregnant Thy1.1 B6 mice were restimulated with irradiated Bm12 splenocytes. The cell-free supernatants of individual wells were removed after 48 h and analyzed by a multiplexed cytokine bead-based immunoassay (20).

Placenta intracellular cytokine staining

Placentae were collected at 13.5 dpc and were cut into small pieces and digested with 1 mg/ml collagenase at 37°C. Single-cell suspension was prepared by passing through the wire mesh. The cells were washed and resuspended in two Percoll fractions at densities of 1.095 and 1.030. The cells in the 1.030 fraction were underlayered with cells in the 1.095 density fraction. The cells were spun at 2500 rpm for 30 min. Cells were taken from the interface, washed, and counted for subsequent flow staining. Pan leukocytes (CD45) expressing Foxp3, IFN-γ, or IL-17 were stained on the surface with anti-CD45 FITC and intracellularly with Foxp3/IFN-γ/IL-17 allophycocyanin (eBioscience) Abs as per the manufacturer’s instructions, then detected by flow cytometry.

Treg conversion in vitro

Thy1.2+Foxp3-GFP+ T cells from ABM Tg.Foxp3-GFP mice, generated in our laboratory by mating ABM tg mice with Rudensky reporter mice (B6 Foxp3-GFP knock-in), were used for in vitro studies. Isolated Foxp3-GFP+ TCR-tg T cells (1 × 10^6) were cocultured with syngeneic CD11c+ cells (0.2 × 10^6), soluble anti-CD28 (1 μg/ml), soluble TGF-β (1 ng/ml), and plate-coated with anti-CD3 (1 μg/ml), in the presence or absence of anti-PDL1 mAb (1, 10, or 50 μg/ml). After 4 d in culture, the percentage of CD4+Foxp3+ cells was assessed by flow cytometry. We also collected the supernatant of these cultures at 48 h to evaluate the production of IL-17 by Luminex. Finally, CD4+GFP+ cells (0.2 × 10^6) from ABM Foxp3-GFP knock-in TCR-tg mice were cocultured with syngeneic CD11c+ cells (0.05 × 10^6) and irradiated Bm12 cells (0.2 × 10^6) in the presence or absence of anti-PDL1. Production of IL-17 was evaluated after 48 h of culture. Cell isolation was performed by FACS-sorting CD4+GFP+, CD4+GFP– cells and CD11c+ cells, resulting in greater than 99% purity.

RNA extraction and RT-PCR

RNA extraction was performed according to the manufacturer’s instructions (Invitrogen). Expression was measured as copies of any given gene divided by copies of the housekeeping gene GAPDH as previously described (14).

Statistics

Kaplan–Meier survival graphs were constructed, and a log rank comparison of means between experimental groups was performed by the log rank test for comparison of means between experimental groups examined by FACS analysis or ELISPOT assay. Differences were considered to be significant at p values <0.05.

Results

Reduction in fetal survival with PDL1 blockade correlates with a decrease in Tregs and Tregs/Teff ratio in the periphery and a lowering of expression of regulatory markers at the uteroplacental interface

To investigate the mechanisms by which the PD1–PDL1 costimulatory pathway affects fetomaternal tolerance, we took advantage of the ABM-tg mouse (21) to track alloantigen-specific CD4+ cells...
with either an effector or a regulatory phenotype development in a Thy1.1 B6 pregnant mouse previously mated with a Bm12 male (see Materials and Methods). We have previously shown that PDL1 is expressed at the fetomaternal interface and that blockade of this molecule resulted in significantly reduced fetal survival rate in a fully allogeneic (CBA × B6) mating setup (11). In this study, we report that PDL1 blockade remarkably increased fetal resorption (34 ± 10 versus 1.4 ± 10%, n = 7, p < 0.0001) and resulted in a reduced litter size compared with control IgG (5.8 ± 0.4 versus 8.5 ± 1, n = 7, p < 0.0001) in the Bm12 × B6 mating as well (Fig. 1).

Subsequently, we adoptively transferred Thy1.2+ABM-ig cells at day 4 after detection of vaginal plug and treated the female mice with either anti-PDL1 mAb or control IgG. We analyzed samples at 11.5 and 13.5 dpc. Flow cytometry analysis demonstrated an increase in the percentage of Thy1.2+Teff (Thy1.2+CD44hiCD62Llow) in spleens of animals treated with anti-PDL1 compared with control IgG (72 ± 1.8 versus 65 ± 1.7%, p < 0.01), particularly at 11.5 dpc, whereas no differences were found at day 13.5 (56 ± 2.7 versus 52 ± 2.8%, p = 0.2). Absolute numbers did not show any difference either at day 11.5 (216,000 ± 25 versus 206,500 ± 13, respectively, p = 0.7) (Fig. 2A) or at day 13.5 (215,000 ± 55 versus 218,400 ± 33, p = 0.9). As shown in Fig. 2B, Thy1.2+Tregs (Thy1.2+CD25+Foxp3+) were also significantly decreased after PDL1 blockade at the same time point in lymph nodes (data not shown) and spleen compartments in both percentage (13 ± 2.7 versus 4 ± 0.7%, p = 0.01) and absolute numbers of cells (382,200 ± 30 versus 217,500 ± 33, respectively, p < 0.01), whereas a less evident reduction was detectable at 13.5 dpc (5.8 ± 0.3 versus 3.9 ± 0.65%, p = 0.03, and 305,300 ± 28 versus 221,595 ± 22, p = 0.048), suggesting a role for this costimulatory pathway in actively regulating the balance between Teff, Tregs, and regulatory molecules in the periphery as well as at the uteroplacental interface.

PDL1 blockade is associated with a switch in Th balance toward Th17

To investigate whether PDL1–PDL1 costimulation is able directly to affect Teff generation and/or tip the Th1/Th2/Th17 balance to promote tolerance during pregnancy, we first analyzed the cytokine profile both locally in the placenta with intracellular cytokine flow staining/RT-PCR and in the periphery with ELISPOT/Luminex-based assays. The most interesting finding was that blocking PDL1 resulted in a major inhibition of Th1 cytokine production both in the periphery (ELISPOT: IFN-γ 24.33 ± 4.717 pg/ml for anti-PDL1–treated mice versus 141.8 ± 29.56 spots per 0.5 × 10⁶ splenocytes of control IgG-treated mice, p < 0.0002; Luminex: IFN-γ-induced protein-10 (IP-10) 20.38 ± 4.8 versus 42.5 ± 7.0 pg/ml, respectively, p < 0.02; TNF-α 51.45 ± 25.67 versus 190.3 ± 12.98 pg/ml, respectively, p < 0.007) and at the uteroplacental interface (TNF-α 0.00002 ± 0.00002 versus 1.17 ± 0.41 copies/copies GADPH, respectively, p < 0.05) with an increase in the production of Th2 cytokines (IL-4 and IL-5) as reported in Fig. 3. Similar results were obtained at the second time point 13.5 dpc for Th1 cytokines (ELISPOT: IFN-γ 91.2 ± 25 for control IgG-treated mice versus 39 ± 6.7 spots per 0.5 × 10⁶ splenocytes of anti-PDL1–treated mice, p = 0.012; Luminex: IP-10 42.5 ± 7 versus 20.38 ± 4.8 pg/ml, respectively, p = 0.019; TNF-α 29.9 ± 6.4 versus 9.53 ± 1.9 pg/ml, respectively, p < 0.001) as well as for Th2 cytokines (ELISPOT: IL-4 88.8 ± 8.6 for control IgG-treated mice versus 114 ± 3.6 spots per 0.5 × 10⁶ splenocytes of anti-PDL1–treated mice, p = 0.018; Luminex: IL-4 21.67 ± 3.4 versus 40.67 ± 6 pg/ml, respectively, p = 0.02; IL-5 51.1 ± 25 versus 153.4 ± 73 pg/ml, respectively, p = 0.010). Notably, we detected a significant increase in IL-6 production at 11.5 dpc and later at 13.5 dpc in anti-PDL1–treated animals compared with controls (11.5 dpc: 285.4 ± 51.7 versus 27.13 ±

![FIGURE 1. PDL1 blockade significantly increases fetal resorption and results in reduced litter size. Thy 1.1 B6 females were mated with Bm12 males, and at days 6.5, 8.5, 10.5, and 12.5, anti-PDL1 mAb or control IgG was injected. Some mice were observed for fetal resorption at 13.5 dpc and others were allowed to go to term and litter sizes counted. A, Scattered dot plots depicting percentages of embryos resorbing in mice treated with anti-PDL1 (n = 7) or control IgG (n = 7). B, Scattered dot plots depicting litter size in mice treated with anti-PDL1 or control IgG are shown.](http://www.jimmunol.org/DownloadedFrom)
3.3 pg/ml, respectively, \( p < 0.0002 \); 13.5 dpc:1579 ± 368.4 versus 741.8 ± 121.7 pg/ml, respectively, \( p < 0.03 \). As it has been reported that IL-6 represents a differentiation factor for Th17 and a target for IL-17–producing cells (23), we examined IL-17 production both locally and in the periphery. As anticipated, ELISPOT and Luminex assays showed a significant increase in the level of IL-17 in the periphery in anti-PDL1–treated mice compared with controls (Fig. 4A). This increase in IL-17 was also demonstrable locally at the uteroplacental interface as evidenced by intracellular flow cytometry staining (Fig. 4B) and by RT-PCR of the placentae of anti-PDL1–treated mice versus control IgG-treated mice (1.1 ± 0.1 versus 0.3 ± 0.05%, \( p < 0.005 \), and 10.36 ± 3.3 versus 1.87 ± 1.2 copies/copies GADPH, \( p < 0.03 \)), as shown in Fig. 4B.

Neutralization of IL-17 abrogates the anti-PDL1 effect on fetal survival rate

Having found differences in Tregs as well as Th17 in our ABM-tg pregnancy model, we focused on delineating the interplay, if any, between Th17 and downmodulation of Tregs in this model. To determine this, we first set up matings between Bm12 males and B6 Thy1.1 females and then treated them with anti-PDL1 alone or in combination with neutralizing antibodies directed against IL-17.
combination with IL-17 neutralizing Ab. Neutralization of IL-17 in anti-PDL1-treated animals showed a significant increase in litter size compared with anti-PDL1 alone (8.6 ± 0.74 versus 4.7 ± 0.14, n = 5 and n = 7, respectively, p < 0.0001) and a significant decrease in fetal resorption (16.2 ± 3.4 versus 37.4 ± 1.7%, n = 5 and n = 7, respectively, p < 0.0002), as represented in Fig. 5A and 5B. We then tested the role of blocking PDL1 in IL-17−/− mice mated with Bm12 males and observed no difference in litter size (8 ± 0.4 versus 8.5 ± 0.8, n = 5, respectively, p = ns) as well as in embryo resorption rate (14.8 ± 4 versus 15.7 ± 2%, n = 5, respectively, p = ns) when animals were treated with anti-PDL1 compared with control IgG (Fig. 5C, 5D). This provided evidence for an important role for IL-17−producing cells in interfering with tolerance induction in this experimental model. Furthermore, it highlights the fact that PDL1 blockade in our single class II-mismatch B6 × Bm12 mating model led to a reduction in fetal survival and an increase in the fetal resorption rate by switching the Th balance in favor of Th17.

Neutralization of IL-17 significantly reduces anti-PDL1-mediated expansion of Teff and abrogates the anti-PDL1-mediated effect in reducing Treg numbers

Our next step was to determine the effect of neutralization of IL-17 in anti-PDL1-treated animals on adoptively transferred Thy1.2 + ABM-tg cells. While the expansion of Thy1.2 + Teff is slightly increased in anti-PDL1−treated animals upon IL-17 neutralization, there is a more marked effect in maintaining Thy1.2 + Tregs compared with administration of anti-PDL1 alone (Fig. 6A, 6B). This results in a relatively increased Treg/Teff ratio compared with that of the group treated with anti-PDL1 alone (Fig. 6C).

**PDL1 blockade inhibits Ag-specific alloreactive T cell apoptosis and induces apoptosis of Tregs**

Because one of the most important mechanisms shown to induce and/or maintain fetomaternal tolerance is the apoptosis of activated maternal cells (2, 24), we investigated its possible link with the PDL1−PDL1 costimulatory pathway. We first focused our attention on the apoptosis of alloantigen-specific ABM-tg cells. Flow cytometry analysis at 11.5 dpc showed that both percentage (5.1 ± 1.6 versus 10.2 ± 1.3%, respectively, p < 0.04) and absolute number (533,546 ± 25 versus 744,170 ± 85, p < 0.05) of Thy1.2 + annexin V + apoptotic cells decreased particularly in the spleen of mice treated with anti-PDL1 compared with control IgG (Fig. 7A, 7B). These data were corroborated by expression of apoptotic markers locally in the placenta by RT-PCR. RT-PCR analysis showed a significant reduction in DR5, a receptor involved in the TRAIL pathway for apoptosis, in the placentalae of anti-PDL1−treated mice versus control IgG-treated mice (0.60 ±

![FIGURE 3. PDL1 blockade results in a suppression of Th1 cytokines and an increase in both Th2 cytokines and IL-6. A. Bar graphs depicting production of allospecific cytokine IFN-γ (by ELISPOT), IP-10 and TNF-α (by Luminex) by splenocytes from Thy1.1 females previously mated with Bm12 males and treated 11.5 dpc with anti-PDL1 or control IgG. Data are representative of three independent experiments using at least n = 4 mice per group. B. Bar graphs depicting production of allospecific cytokine IL-4 (by ELISPOT), IL-4 and IL-5 (by Luminex) by splenocytes from Thy1.1 females previously mated with Bm12 males and treated 11.5 dpc with anti-PDL1 or control IgG. Data are representative of three independent experiments using at least n = 4 mice per group. C. Bar graphs depicting production of allospecific cytokine IL-6 (by Luminex) by splenocytes from Thy1.1 females previously mated with Bm12 males and treated 11.5 dpc with anti-PDL1 or control IgG. Data are representative of three independent experiments using at least n = 4 mice per group.](http://www.jimmunol.org/Downloadedfrom)
obtained from three separate experiments. Pregnant mice treated as above, with representative flow plots in each treatment group shown on the right panel. The ELISPOT assay was performed to detect IL-17–secreting cells. Splenocytes from pregnant Thy1.1 B6 mice were irradiated and used as stimulator cells. The ELISPOT assay was performed in anti-PDL1 mAb or control IgG Ab group by RT-PCR or by flow cytometry. For placenta intracellular cytokine staining, placentae were collected at 13.5 dpc and were digested with collagenase at 37˚C and processed to obtain infiltrating cells as described in Materials and Methods. Pan leukocytes (CD45) expressing IL-17 were stained on the surface with anti-CD45 FITC and intracellularly with anti–IL-17 allophycocyanin Abs and detected by flow cytometry. B, Left panel, Scatter plots depicting expression of IL-17 cytokine by RT-PCR at the fetomaternal interface of pregnant mice treated as above. Middle panel, Bar graphs depicting detection of IL-17 cytokine by intracellular cytokine staining at the fetomaternal interface of pregnant mice treated as above, with representative flow plots in each treatment group shown on the right. The data represent the mean ± SD of the results obtained from three separate experiments.

CD4+Foxp3+ cells in the presence or absence of anti-PDL1 mAb. Our in vitro data show that anti-PDL1 decreases conversion of CD4+Foxp3+ cells into CD4+Foxp3+ Tregs. This decrease in conversion is small but significant (p < 0.01) (Fig. 8A). Moreover, PDL1 blockade increases the frequency of IL-17–producing cells from CD4+Foxp3− cells in a dose-dependent manner (Fig. 8B). However, when CD4+Foxp3+ Tregs were cultured in the presence of anti-PDL1 mAb, they failed to convert to Th17-producing cells (Fig. 8C).

To strengthen our in vitro findings, we used ABM Tg.Foxp3-GFP mice in which Ag-specific Tregs (CD4+Thy1.2+Foxp3-GFP+) can be detected, isolated, and adoptively transferred. Flow-sorted Thy1.2+CD4+Foxp3-GFP+ (Tregs) and GFP− cells (0.3 × 106) were injected i.p. into Thy 1.1 B6 female mice mated with Bm12 males and treated with either anti-PDL1 or control IgG. We then harvested these cells 72 h after injection to evaluate their fate (Supplemental Fig. 2). About 15–20% of injected cells were present on secondary lymphoid organs 3 d after injection (Fig. 9A). Whereas both control and anti-PDL1–treated groups lost Foxp3 expression after transfer of Thy1.2+CD4+Foxp3-GFP+ cells to new recipients (Fig. 9B), the group treated with anti-PDL1 showed a greater conversion to Foxp3-GFP+ cells (Fig. 9B). Moreover, IL-17 production was very low on both groups, refuting the hypothesis of increased conversion of Foxp3-GFP+ cells into Th17 cells in the setting of PDL1 blockade (Fig. 9E). After transfer of Foxp3-GFP+ cells, we observed about a 5% conversion to Foxp3-GFP+ cells in...
both groups (Fig. 9D). Notably, we noticed an increased conversion of Foxp3-GFP<sup>+</sup> cells into IL-17–producing T cells (Fig. 9F), in agreement with our in vitro data above. Overall, these data show that PDL1 blockade increases the conversion of Foxp3-GFP<sup>+</sup> cells into IL-17–producing cells and decreases the number of Tregs but does not seem to convert Tregs into IL-17–producing T cells.

To confirm the role of Tregs in PDL1-induced fetomaternal tolerance, we performed similar adoptive transfer of Thy1.2<sup>+</sup>Foxp3-GFP<sup>+</sup> (Tregs) and GFP<sup>+</sup> cells from ABM Tg.Foxp3-GFP mice into Thy 1.1 B6 female mice mated with Bm12 males and treated with either anti-PDL1 or control IgG. However, this time we evaluated the pregnant B6 mice for litter size. A group of control mice without any adoptive transferred cells was also set up, and litter size of all groups was assessed. The litter size in Thy1.1 B6 females treated with anti-PDL1 mAb was close to six pups per litter. After transfer of Tregs, there was a significant increase in the litter size in this group to eight pups per litter (p < 0.0033) (Fig. 9G). There was no increase in the control IgG-treated group receiving Tregs versus not receiving any Tregs (Fig. 9G). This could presumably be because of no defect in the litter size in the control IgG group, and hence an additional dose of Tregs did not change the litter size outcome. This beneficial effect was specific to GFP<sup>+</sup> cells as transfer of GFP<sup>+</sup> cells into anti-PDL1 or control IgG-treated Thy1.1 B6 (mated with Bm12) mice did not result in rescue of phenotype in the anti-PDL1 group (litter size, 5.0 ± 0.71 in GFP<sup>+</sup> plus anti-PDL1 versus 5.0 ± 0.91 in no cells plus anti-PDL1 group; n = 4, p = ns). Litter size in GFP<sup>−</sup> cells plus control IgG and no cells plus control IgG was normal and close to eight pups per litter.

**Discussion**

In this report, we demonstrate that PDL1 blockade reduces fetal survival rate by affecting various immune cells and regulatory molecules both in the periphery and at the uteroplacental interface. For this purpose, we used an alloantigen-specific CD4<sup>+</sup> transgenic model with a Bm12<sup>+</sup>B6 mating. First, PDL1 blockade inhibits the negative regulation of the immune response against alloantigens and contributes to fetomaternal tolerance by controlling alloantigen-specific Tregs in vivo in the periphery. The immunoregulatory role of the PD1–PDL1 costimulatory pathway in peripheral tolerance has previously been described in a fully allogeneic heart transplantation model (25) and in a class II mismatch model of skin transplantation (26). In both cases, PDL1 blockade resulted in an acceleration of allograft rejection. This was attributed to either a failure in immune regulation as a result of a decrease in Treg numbers and/or ineffective suppressive effect. Wang et al. (27) demonstrated that the deficiency of PDL1 molecules alters the balance of peripheral lymphocytes by decreasing the number of Tregs. In addition, there is an increase in the number of APCs that express a higher level of costimulatory molecules, thereby enhancing allogenic immune responses in PDL1<sup>−/−</sup> recipients and accelerating heart allograft rejection (27). In this study, we did not look specifically at the APCs. Kitazawa
et al. (28) have recently shown that the PD1–PDL1 pathway is required for Tregs effectively to suppress the alloreactive responses of Teff. In addition, PDL1 expression by dendritic cells is necessary for the induction of Foxp3+ adaptive Tregs both in vitro and in vivo (29). Finally, the PD1–PDL1 costimulatory pathway and Tregs have been demonstrated to participate strictly in the development of fetomaternal tolerance (14) and in the prevention of fetal rejection in an abortion-prone experimental model of murine pregnancy (30).

In contrast, our results document that PDL1 blockade also modulates the balance of alloimmune response locally at the fetomaternal interface with the involvement of different molecules and pathways. In line with this, Yang et al. (31) demonstrated that PDL1 blockade in Bm12 into B6 heart transplant significantly accelerates chronic rejection depending on the expression of PDL1 on donor tissue that regulates recipient alloimmune responses. Similarly, Tanaka et al. (10) described a shift in the balance between Tregs and Teff in favor of Teff during PDL1 blockade in a fully allogeneic heart transplant due to an inhibition of the delivery of the negative costimulatory signal and also showed that PDL1 expression in donor tissue was essential to prevent graft infiltration and rejection.

**FIGURE 6.** Neutralization of IL-17 significantly reduces anti-PDL1–mediated expansion of effector cells and abrogates anti-PDL1–mediated reduction of Tregs. Spleens and lymph nodes were harvested from ABM TCR-tg mice, and CD4+ T cells were purified and tested for expression of the tg TCR as determined by anti-TCR Vα2.1 and anti-TCR Vβ8.1 Ab staining. ABM TCR-tg CD4+ T cells (3 × 10^6) were then injected i.p. into Thy 1.1 B6 females mated with Bm12 males (day 0), and mice received either anti-PDL1 or control IgG. Neutralizing IL-17 mAb was administered to some of the mice treated with anti-PDL1 Ab. On 11.5 dpc, lymph nodes and spleens were collected, single-cell leukocyte suspensions were prepared, and ABM TCR-tg T cells were identified by staining for CD90.1.2 (Thy1.2) surface marker at flow cytometry. A, Bar graphs depicting absolute numbers of Thy1.2–Teff in spleen of adoptively transferred pregnant mice at 11.5 dpc with various treatments. Data are representative of three independent experiments using at least n = 4 mice per group. B, Bar graphs depicting absolute numbers of Thy1.2–Tregs in spleen of adoptively transferred pregnant mice at 11.5 dpc with various treatments. Data are representative of three independent experiments using at least n = 4 mice per group. C, Scattered dot plots depicting Tregs/Teff ratio (absolute numbers of cells) in pregnant mice at 11.5 dpc with various treatments.
Our results in the alloantigen-specific model also support the role for PD1–PDL1 costimulation in promoting Ag-specific Tregs and in limiting Ag-specific Teff expansion in the context of fetomaternal tolerance.

Furthermore, our data suggest that PD1–PDL1 costimulation also contributes to the maintenance of fetomaternal tolerance by promoting apoptosis of maternal Ag-specific activated cells. It has been reported earlier that the PD1–PDL1 costimulatory pathway plays an important role in fetomaternal tolerance by inducing apoptosis of paternal Ag-specific T cells and that PD1 action is the main mechanism that prevents T cell accumulation in lymph nodes (32). In addition to that, a study from Bai et al. (33) on the TRAIL apoptotic pathway in humans showed that DR5 expression on cytotrophoblast cell surface promotes susceptibility to apoptosis and that lack of DR5 cell surface expression may direct TRAIL-induced cytotoxicity away from the placenta and toward the maternal system. This is in accordance with our observation that DR5 expression at the fetomaternal interface is reduced in anti-PDL1–treated animals and accounts for a diminished responsiveness to TRAIL-mediated apoptosis.

As part of PD1–PDL1 immunomodulatory function, our study also shows that PDL1 blockade is associated with a switch in Th
balance toward Th17, which leads to a reduction in fetal survival and increase in the fetal resorption rate in our single class II mismatch B6 × Balb/c mating model. Habicht et al. (14) described a similar increase in IL-17 production in the placenta of PDL1 knockout female mice compared with wild-type (B6) control mice in the absence of anti-PDL1 mAb. After 4 d in culture, the percentage of CD4+Foxp3+ cells was assessed by flow cytometry. For the Treg conversion, CD4+Foxp3+ cells from ABM Tg.Foxp3-GFP mice were cultured for 48 h with syngeneic CD11c+ cells and irradiated Bm12 cells in the presence or absence of anti-PDL1. A, Bar graphs depicting in vitro conversion of CD4+Foxp3+ cells into CD4+Foxp3-GFP+ cells incubated with anti-PDL1 Ab. Below the bar graphs, representative flow histograms of Foxp3-GFP+ cells gated on CD4+ cells are shown. B, Bar graphs depicting IL-17 production from CD4+Foxp3-GFP+ cells incubated with anti-PDL1 Ab in a dose-dependent manner. C, Bar graphs depicting IL-17 production from CD4+Foxp3GFP+ cells incubated in vitro with anti-PDL1 Ab at multiple concentrations.

In summary, it has been shown that Tregs are able to prolong graft survival not only because of their suppression of Teff but also because of their anti-inflammatory properties (39). It has also been reported that Tregs represent a key mechanism in inducing fetal acceptance during pregnancy both in mice and humans (6, 40). PD1–PDL1 negative costimulation mediates the induction of peripheral tolerance both in a transplantation model as well as in a fetomaternal experimental model by favoring the regulatory function exerted by Tregs (9, 10, 13, 14, 30). In this study, we show that PDL1 blockade is associated with a reduction in the absolute number of Tregs. This results in a failing suppressive effect on alloreactive T cells and in particular in those producing IL-17. Different mechanisms have been reported in an attempt to explain the link between PDL1 and Tregs. Francisco et al. (8) described a direct role for PDL1 in regulating induced Treg development and function. The authors showed that in the absence of PDL1, naive CD4+ T cells minimally convert to Tregs, and PDL1 itself enhances and sustains Foxp3 expression and the suppressive function of induced Tregs (8). Despite our initial in vitro findings suggesting similar effect, our adoptive transfer experiments in vivo did not show a significant decrease in conversion in the setting of PDL1 blockade. Possible explanations for the divergent results might be related to the number of Tregs transferred, timing of analysis, or model used. Nonetheless, other authors have suggested that the expression of PDL1 on tumor cells exerts an antiapoptotic effect and renders them resistant to apoptosis (37, 38), which findings are in accordance with the observed increased apoptosis of Tregs in our results.

Therefore, we focused mainly on confirming the role of IL-17 in contributing to fetal rejection and its complex interplay with both PD1–PDL1 costimulation and Tregs modulation in interrupting the state of tolerance. Our study demonstrates that neutralization of IL-17 abrogates the anti-PDL1 effect on fetal survival rate. It also confirms a detrimental role for IL-17–producing cells in promoting and sustaining fetal rejection as evidenced by the IL-17 knockout data. Our data with these mice indicate that IL-17–producing cells play a major role in disrupting the state of tolerance early on, but further studies are necessary to investigate the exact mechanism in detail.

Moreover, it has been shown that PDL1 blockade in transplantation is correlated with a net increase in alloreactive T cells due to a reduction in apoptosis mechanisms. It has also been correlated with a reduction in Tregs and a decreased Treg suppressive effect (9, 26). In this study, we show that PDL1 blockade is associated with a reduction in the absolute number of Tregs. This results in a failing suppressive effect on alloreactive T cells and in particular in those producing IL-17. Different mechanisms have been reported in an attempt to explain the link between PDL1 and Tregs. Francisco et al. (8) described a direct role for PDL1 in regulating induced Treg development and function. The authors showed that in the absence of PDL1, naive CD4+ T cells minimally convert to Tregs, and PDL1 itself enhances and sustains Foxp3 expression and the suppressive function of induced Tregs (8). Despite our initial in vitro findings suggesting similar effect, our adoptive transfer experiments in vivo did not show a significant decrease in conversion in the setting of PDL1 blockade. Possible explanations for the divergent results might be related to the number of Tregs transferred, timing of analysis, or model used. Nonetheless, other authors have suggested that the expression of PDL1 on tumor cells exerts an antiapoptotic effect and renders them resistant to apoptosis (37, 38), which findings are in accordance with the observed increased apoptosis of Tregs in our results.
that skewing the response toward Th17 away from Tregs by inhibiting PDL1 costimulation can be crucial in breaking fetomaternal tolerance, and this effect seems to be mediated by a conversion of CD4+Foxp3 cells to Th17 cells and increased apoptosis of Tregs. Furthermore, the neutralization of IL-17 or the adoptive transfer of Ag-specific Tregs is able to abrogate the deleterious effect of PDL1 blockade. Therefore, PDL1 expression may represent the key factor in balancing Tregs and Th17 cells and maintaining tolerance at the fetomaternal interface. Further studies are urged to assess a possible role for PD1–PDL1 co-stimulation in affecting the interplay between Tregs and Th17 in allograft rejection during transplantation.

Disclosures
The authors have no financial conflicts of interest.