Human CD4⁺CD25low Adaptive T Regulatory Cells Suppress Delayed-Type Hypersensitivity during Transplant Tolerance


Adaptive T regulatory (T₉) cells mediate the suppression of donor-specific, delayed-type hypersensitivity (DTH) in tolerant organ transplant recipients. We hypothesized that cells belonging to the CD4⁺CD25⁺ T cell subset but distinct from natural T₉ cells may fulfill this role. To test this hypothesis, PBMC and biopsy samples from two tolerant kidney transplant recipients (K1 and K2) were analyzed. When transferred with recipient APC into a SCID mouse footpad, CD4⁺ T cells were hyperresponsive in DTH to donor type HLA-B Ags and derivative allopeptides. However, anti-human TGF-β1 Ab revealed a response to immunodominant allopeptides in both patients, suggesting that CD4⁺ T effector (Tₑ) cells coexisted with suppressive, TGF-β1-producing CD4⁺ T₉ cells. During in vitro culture, allopeptide stimulation induced both IFN-γ-producing and surface TGF-β1⁺ T cells. The relative strength of the latter response in patient K1 was inversely correlated with the level of systemic anti-donor DTH, which varied over a 6-year interval. Allopeptide-induced surface TGF-β1 expression was found primarily in Forkhead box P3 (FoxP3)⁻negative CD4⁺CD25low T cells, which could adoptively transfer suppression of donor-specific DTH. Biopsy samples contained numerous surface TGF-β1⁺ mononuclear cells that costained for CD4 and, less frequently CD25, but were negative for FoxP3. The CD4⁺TGF-β1⁺ T cells were localized primarily to the tubulointerstitium, whereas TGF-β1⁺FoxP3⁺CD25⁺ cells were found mainly in lymphoid aggregates. Thus, adaptive Tₑ cells suppressing Tₑ cell responses to donor allopeptides in two tolerant patients appear to be functionally and phenotypically distinct from CD4⁺CD25highFoxP3⁺ T cells. The Journal of Immunology, 2007, 178: 3983–3995.

H omeostatic equilibrium between Ag-specific T regulatory (T₉) cells and T effector (Tₑ) cells has been proposed to account for certain paradoxical features of the adaptive immune system. For example, the preservation of immunocompetent T memory cells in chronic parasite or viral infection (1, 2) has been attributed to a Tₑ-dominant Tₑ-T₉ homeostasis, as has the protection of malignant melanoma from tumor Ag-specific rejection (3), the maintenance of transplantation tolerance (4–6), the control of inflammatory bowel disease (7), the TGF-β1⁻dependent reversal of recent onset diabetes by anti-CD3-antibody in the NOD mouse (8), and the beneficial effects of anti-CD3 mAb ther-
T<sub>R</sub> cells (20, 22), yet they can also suppress T<sub>R</sub> cell-driven delayed-type hypersensitivity (DTH) responses by means of TGF-β1 production (20, 23, 24). These features allow clear distinctions to be made between adaptive T<sub>R</sub> and T<sub>R</sub> cells.

Based on previous work in rhesus macaques (4) and humans (20, 25), we have proposed a model of tolerance to an organ allograft that is based on a dynamic equilibrium between alloantigen-specific T<sub>R</sub> cells and T<sub>R</sub> cells (26). Adoptive transfer studies of selected T cell populations combined with transplantation may be used to test such a mechanism in animal models, breaking tolerance as needed and then rescuing with infusions of T<sub>R</sub> cells. However, in human studies such an approach is not feasible. One way to test such a model in the clinical transplant setting would be to take advantage of the metastable nature of tolerance itself in the course of a long-term follow-up. For example, by leukapheresis (LKP) and cryopreservation of PBMC at different times posttransplant one may compare putative T<sub>R</sub> and T<sub>R</sub> cell fractions from time points of anti-donor hyporesponsiveness when the equilibrium between donor-specific T<sub>R</sub> and T<sub>R</sub> cells favors the T<sub>R</sub> and contrast this with the same cell fractions obtained during a period of high responsiveness to a donor when such an equilibrium has broken down. The adoptive transfer can then be done using a surrogate in vivo assay system such as the trans-vivo DTH test (20, 27).

We hypothesized that human adaptive CD4<sup>+</sup> T<sub>R</sub> cells, which recognize cognate allopeptide/self-MHC complexes via the indirect allore cognition pathway, are functionally and phenotypically distinct from FoxP3<sup>+</sup> CD4<sup>+</sup> T<sub>R</sub> cells. To test this hypothesis, we used PBMC from two patients with HLA-mismatched kidney transplants and stable renal function >2 years after discontinuing all immunosuppression. We were also able to monitor one of these patients over a 6-year period after initial enrollment in our study. By flow cytometry, flow sorting, and functional assays, we found that the CD4<sup>+</sup>CD25<sup>+</sup> subset of PBMC in both patients contained surface TGF-β1-inducible, allopeptide-specific T<sub>R</sub> cells, whereas PBMC from an HLA-B-sensitized patient, K3, lacked such cells. These T<sub>R</sub> cells were able to suppress anti-donor DTH reactions while CD4<sup>+</sup>CD25<sup>+</sup> cells did not. Furthermore, immunohistochemical analyses of biopsy samples indicated that CD4<sup>+</sup> TGF-β<sup>+</sup> T<sub>R</sub> cells in the accepted allograft occupy a niche anatomically distinct from that of FoxP3<sup>+</sup>CD25<sup>+</sup> T<sub>R</sub> cells during allograft tolerance.

Materials and Methods

**HLA typing and source of PBMC**

PBMC were obtained by sterile venipuncture or LKP, further purified by Ficoll-Hypaque density gradient separation, and cryopreserved until use. All blood and LKP samples were obtained by informed consent subject to Institutional Review Board (University of Wisconsin, Madison, WI) approval. HLA-A and -B typing was performed by standard complement-dependent cytotoxicity techniques; for patient K1 and donor HLA-B serologic typing was confirmed by high resolution sequence-specific primer PCR, whereas HLA-DR/DQ typing was performed by low resolution sequence-specific PCR.

**Ags and peptide preparation**

The donor Ag was either a cell sonicate of donor PBMC, a cell sonicate of the 721.221 lymphoblastoid cell line singly transferred with donor-type HLA (B8, B7), or a soluble recombinant HLA-B*1501 (B62). Donor Ags were prepared and used with methods described previously (25, 28, 29). Recall Ags such as tetanus toxoid (TT; Lederle Laboratories) and EBV (Viral Antigens) were used as described (25, 28). Four 18-mer oligopeptides were synthesized and purified (≥94% pure) at the Biotechnology Facility at the University of Wisconsin (Madison, WI).

**Flow cytometric analysis and cell sorting**

All anti-human mAbs and secondary reagents for flow cytometric analysis, if not specifically noted, were obtained from BD Pharmingen. Flow cytometry was performed on a FACSCalibur or SLR II (BD Biosciences), analyzed with CellQuest (BD Biosciences), or FlowJo (Tree Star) software. CD4<sup>+</sup> and CD8<sup>+</sup> T cells (purity >98%) were sorted from whole PBMC by FACSVantage (BD Biosciences) with CD4<sup>+</sup>FITC/CD8<sup>+</sup>PE mAbs (Beckman Coulter). Different fractions of CD4<sup>+</sup>CD25<sup>+</sup>/low<sup>+</sup> cells (purity ≥98%) were flow sorted from whole PBMC or MACS-enriched CD4<sup>+</sup> T cells. For certain experiments CD4<sup>+</sup> or CD8<sup>+</sup> T cells were also MACS-depleted using anti-CD4/CD8 beads (Miltenyi Biotec); depletion was typically ≥99% of starting CD4 or CD8 T cells.

**Cell culture and surface TGF-β1 staining**

PBMC (8 × 10<sup>6</sup>/well) or CD4<sup>+</sup>CD25<sup>+</sup>CD4<sup>+</sup> cells (1–2 × 10<sup>5</sup> cells/well) plus irradiated CD4<sup>+</sup> cells (<0.5% CD4<sup>+</sup> T cells used as APC, 10<sup>6</sup>/well) were cultured with peptides or anti-CD3 (clone OKT3; 10 μg/ml) in 100 μl/well IMDM (Cambrex) with 2% Serum Replacement 3 (Sigma-Aldrich), t-glutamine, 1 mM sodium pyruvate, and 2% penicillin-streptomycin for 40 h at 37°C with 5% CO<sub>2</sub> and stained with biotinylated chicken anti-human TGF-β1 (R&D Systems) or biotinylated chicken IgY control (Jackson ImmunoResearch Laboratories) and secondary reagents. The specific induction of surface TGF-β1<sup>+</sup> cell was determined by subtracting the background percentage of the TGF-β1<sup>+</sup> value for self-peptide p37-TE-stimulated cells (where TE refers to threonine and glutamic acid). Rat anti-human FoxP3-FITC (clone PCH101; ebiosisceinc) and rat IgG2a (BD Pharmingen) were used with the protocol described by the vendor.

**Trans-vivo DTH assay**

The trans-vivo DTH assay was used as described (25). Ags (1 μg/ml) were injected along with 9 × 10<sup>6</sup> whole PBMC (or CD4/CD8-depleted PBMC) or 3–4 × 10<sup>6</sup> separated T lymphocytes plus 8 × 10<sup>6</sup> Percoll-purified APC into the footpads of female CB17 SCID mice (Harlan Breeder). In some experiments, RAG2−/−/TGF-β<sup>−/−</sup> single-knockout mice or RAG2−/−/TGF-β<sup>−/−</sup> double-knockout mice bred from a line of RAG2−/−/TGF-β<sup>−/−</sup> parental mice on a C57BL/6 × 129 hybrid background and provided by Dr. T. Doetschman (University of Cincinnati College of Medicine, Cincinnati, OH) were used. Animals were housed and treated in accordance with American Association of Laboratory Animal Care and National Institutes of Health guidelines. In linked suppression assays, recall Ags (such as TT and EBV) were coincubated with PBMC alone or with donor Ag to detect donor-specific T<sub>R</sub> cells. To reveal suppressed DTH responses, rabbit anti-human TGF-β (pan-specific) or control normal rabbit IgG (R&D Systems) was used for cytokine neutralization experiments if not specifically noted otherwise; anti-human CTLA-4 blocking mAb/control mouse IgG1 (Ab Solutions) was also used to reverse suppression. For a DTH assay with purified T<sub>R</sub> cells, APC (purity of >90% CD14<sup>+</sup>) were enriched from PBMC by discontinuous Percoll density gradient centrifugation as described previously (30). Residual T and B cells were depleted by incubating the 1.062 density fraction with mouse anti-human CD2 and mouse anti-human CD20 (Beckman Coulter), followed by goat anti-mouse-IgM magnetic beads (Dynal) separation.

DTH results are reported as mean ± SD of 2–10 independent experiments measuring changes in footpad thickness in units of 10<sup>−4</sup> inches 24 h postinjection after subtraction of background swelling due to the injection of PBMC plus PBS alone.

**Anti-HLA Ab detection**

Anti-HLA Abs were detected in human serum by indirect immunofluorescence using fluorescence-labeled beads coated with single HLA class I or class II Abs (Luminex single HLA Ab test kit, One Lambda). Specific immunofluorescence values for a given batch of beads vary; therefore, results are reported as a ratio of specific Ag-to-background fluorescence for each clinical specimen tested.

**ELISPOT assay**

An IFN-γ ELISPOT assay was performed as described elsewhere (31). Briefly, 96-well polystyrene flat-bottom microtiter plates (Whatman) were coated with anti-human IFN-γ capture Ab (5 μg/ml; BD Pharmingen). Human PBMC (3 × 10<sup>5</sup>/well) were plated with different peptides (300 μg/ml BD Pharmingen). After incubation at 37°C with 5% CO<sub>2</sub> for 48 h, a secondary Ab (2 μg/ml; BD Pharmingen) was added and then developed with ELISPOT Blue Color Module (R&D Systems) and read with the AID ELISPOT reader system ELR02 (Cell Technology).
HLA-A,-B,-DR typing and description of patients and donors

<table>
<thead>
<tr>
<th>Patients</th>
<th>Donor</th>
<th>Recipient</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>A1, 2; B44, 62; DR4, 6+</td>
<td>A1, 2; B37, 60; DR4, 6+</td>
</tr>
<tr>
<td>K2</td>
<td>A2, 26; B8, 57; DR2, 7</td>
<td>A2, 26; B14, 22; DR1, 6+</td>
</tr>
<tr>
<td>K3</td>
<td>A2, 3; B7, 62; DR13, 15</td>
<td>A2, 3; B7, 8; DR4, 15</td>
</tr>
<tr>
<td>L1</td>
<td>A25, 28; B47, 62; DR4, 7</td>
<td>A2, 29; B7, 44; DR15, 6+</td>
</tr>
</tbody>
</table>

- Underlined designations indicate tolerant transplant recipients.
- Kidney transplant from a deceased donor in 1993 for reflux nephropathy. Off insulin in 1995; clinical course described as patient DS elsewhere (25) and in Fig. 3.
- Serologically defined HLA-B Ag. By molecular typing this was designated as B*1501.
- HLA-DR molecular type DRB1*0101, *1301.
- HLA-DR molecular type DRB1*0407, *1301.
- Kidney transplant from a deceased donor in 1986 for chronic glomerulonephritis; ceased insulin in 2003 due to renal carcinoma in native kidney that was removed in 2004. Current serum creatinine is 1.1 mg/dl.
- HLA-DR molecular type DRB1*0102, *1302.
- Kidney transplant from haploidentical sibling as part of a tolerance induction trial, currently on rapamycin monotherapy. Current serum creatinine is 1.3 mg/dl.
- Liver recipient in 1986 currently on triple therapy with prednisone, mycophenolate mofetil, and tacrolimus; described as patient BK previously (28).

H&E histopathology and TGF-β FoxP3 immunohistochemistry

Biopsies were graded according to the Banff criteria (32) of renal allograft pathology on H&E staining of paraffin-embedded tissue. Paraffin-embedded or frozen sections of biopsy were immunolabeled using mAbs against TGF-β1 (clone TB21) as described (4). For paraffin sections only the heat-induced epitope retrieval method (33) with an EDTA buffer (pH 8.0) (Borg; Biocare Medical) was used. Fluorescent immunolabeling was performed as described (4) with anti-CD4, anti-CD-8, and anti-CD25 at a 1/4 dilution. Sections were visualized with a fluorescent microscope (Olympus BX51) and images analyzed with image software (Diagnostic Instruments, version 3.2.1).

For immunoperoxidase dual labeling studies, FoxP3 (rabbit anti-human polyclonal; Abcam Ab 10563) and CD25 (mouse anti-human monoclonal; Vector VP-C340) as well as TB21 Abs were used on paraffin-embedded tissue after EDTA heat-induced epitope retrieval of Ag. The primary Ab to TGF-β1 or CD25 (1/40 dilution) was incubated for 1 h at room temperature, detected with Mach 2 (Biocare Medical) and color developed with Vector VP-C340 and TB21 Abs. For paraffin sections only the heat-induced epitope retrieval method (33) with an EDTA buffer (pH 8.0) (Borg; Biocare Medical) was used. Fluorescent immunolabeling was performed as described (4) with anti-CD4, anti-CD-8, and anti-CD25 at a 1/40 dilution. Sections were visualized with a fluorescent microscope (Olympus BX51) and images analyzed with image software (Diagnostic Instruments, version 3.2.1).

Statistical analysis

Statistical analysis was performed using a randomization test if not specified or noted otherwise. The randomization test based on t statistics is much more stringent than the standard t test; it is used when evaluating reproducibility of results within experiments using samples drawn from a single patient.

Results

DTH responses to donor HLA-B Ag are CD4 mediated and inhibited by TGF-β1

The HLA-A,-B, and -DR Ags of donors and recipients are shown in Table I. Both of the kidney transplant patients, K1 and K2, were functionally tolerant, i.e., off all immunosuppression for >2 years while retaining excellent kidney function. Patient K1 received a graft from a well-matched HLA-DR/DQ but HLA-B44 and B62 (B*1501)-mismatched deceased donor in 1993. Patient K2 received a graft from a deceased donor in 1986 that was mismatched for 5/6 HLA-A, -B, and -DR Ags, including HLA-B8 and HLA-B57. Patient K3, who developed anti-B*1501-specific HLA Ab in the first year posttransplant, is included as a nontolerant control. A conventionally immunosuppressed recipient of a liver transplant from a fully HLA-mismatched deceased donor (29), patient L1, was included in the study to compare allopeptide specificity of the indirect pathway CD4 T cell response to the same HLA-B Ag in a different host MHC class II context.

To characterize the indirect pathway of allore cognition of HLA-B Ags, we injected purified soluble HLA proteins or cell lysates containing soluble HLA together with PBMC into the footpads of SCID mice. The PBMC of patient K1 responded weakly to soluble HLA-B*1501 Ag as measured in units of 10–4 inches net footpad swelling (n = 2–4 experiments).

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A slightly different approach yielded a similar result in patient K2. Patient K2 was EBV sero-negative and did not respond to DTH to the EBV Ag (data not shown). We could therefore use cell sonicates of the B lymphoblastoid cell line 721.221, a HLA class I “null” mutant cell line, and sublines transfected with particular HLA-B genes to probe the memory T cell response of K2 to
HLA-B Ags without complication from responses to EBV proteins expressed in the cell lysates. TGF-β1 neutralization restored a positive DTH response in whole PBMC to HLA-B*0801 but not to a third party Ag HLA-B*0702 or to HLA class I-negative, 721.221 cell sonicates. The restoration of response to HLA-B*0801 in the presence of an anti-TGF-β1 Ab was abrogated by the depletion of CD4+ but not by depletion of CD8+ T cells (Fig. 1B). Thus, in each case the TE cells that responded to donor-type soluble HLA Ags when TGF-β1 was neutralized were CD4+. The anti-IL-10 Ab, which blocks TR and restores TE cell function in some transplant recipients (25), was also tested but did not reveal a significant anti-donor DTH response in these two subjects (data not shown).

A reversal of DTH hyporesponsiveness to HLA-B*1501 in the PBMC of patient K1 by an anti-TGF-β1-specific Ab was also seen in the footpad of a RAG-2/TGF-β1 double-knockout mouse, indicating that murine TGF-β1 was not required for the suppression of B*1501-specific TE function in K1 PBMC (Fig. 1C).

Table II. HLA-B peptide sequences

<table>
<thead>
<tr>
<th>HLA-B Ag</th>
<th>Peptide</th>
<th>Amino Acid Sequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>B*1501</td>
<td>p106 (p106–123) self</td>
<td>NH2–DGRLLLGHDCQAYDGKDY–COOH</td>
</tr>
<tr>
<td>B*1501</td>
<td>p149 (p149–166) self</td>
<td>NH2–AAAREAEQWRAYLEGCLVE–COOH</td>
</tr>
<tr>
<td>B<em>1501; B</em>5701</td>
<td>p37-MA (p37–54) self</td>
<td>NH2–DSDAASPPMAAPRPWIEQ–COOH</td>
</tr>
<tr>
<td></td>
<td>p37-TE (p37–54) allo</td>
<td>NH2–DSDAASPRTEPAPWIEQ–COOH</td>
</tr>
<tr>
<td>B*0801</td>
<td>p61-F (p61–77) self</td>
<td>NH2–DRTQIFKNTQTDRS–COOH</td>
</tr>
<tr>
<td></td>
<td>p61-C (p61–77) allo</td>
<td>NH2–DRTQIKTKNTQTDRS–COOH</td>
</tr>
</tbody>
</table>

* For the peptide defined by the region from aa 37 to aa 54 we designated the donor allopeptide p37-MA where “MA” refers to the polymorphic residues methionine and alanine at positions 44 and 45 (in boldface type), whereas the corresponding “self” peptide p37-TE has threonine and glutamic acid. The MA polymorphism is found predominantly in only two common Caucasian HLA-B Ags, HLA-B*1501 and HLA-B*57, a mismatched HLA-B Ag for patient K2.

The polymorphic phenylalanine (F) amino acid is present at position 67 (in boldface type) in all HLA-B8 family members, whereas the cysteine (C) amino acid (boldface type) is present in the HLA-B14 of patient K2.

Allopeptide specificity of donor HLA-B-reactive CD4+ T_R and T_E cells

To further define the specificity of the DTH response of CD4+ T cells to donor-type HLA-B Ags, four allopeptides and two self-peptides were synthesized based on a comparison of donor and recipient HLA-B amino acid sequences and the identification of polymorphic residues that differed between the two (Table II). We compared responses to HLA-B*1501- or HLA-B*0801-derived allopeptides in the presence of a control rabbit IgG or an anti-TGF-β1 Ab. PBMC from patient K1 contained T_R capable of mediating a strong DTH response to the peptide p37-MA (where MA refers to methionine and alanine) but not to p106 or p149. This response required recipient APC (data not shown). The level of DTH response to p37-MA when TGF-β1 was neutralized was equivalent to the response to intact soluble HLA-B*1501 Ag, indicating that the p37 peptide contained the immunodominant epitope (compare Fig. 2A with Fig. 1A). In the conventionally immunosuppressed liver transplant recipient L1, also mismatched for HLA-B*1501 with her donor, a positive DTH response was revealed by TGF-β1 neutralization when PBMC were challenged with soluble HLA-B*1501, p106 (weakly), and p149, but there was no response to p37-MA (Fig. 2A, right panel). These results indicate that the CD4 T cells in patients K1 and L1 recognized different immunodominant epitopes, consistent with the difference in their HLA-DR alleles (Table I). In patient K2, TGF-β neutralization revealed a significant (p < 0.01 vs control antibody) DTH response to the HLA-B*0801 allopeptide p61-F, and, surprisingly,
DTH data for LKP are the mean renal allograft at year 4.5.

**Left panel**

Green staining identifies CD4/H11003 in paraffin-embedded section (600 original magnification).

Dual immunofluorescence study of TGF-β1/neutrophil (N) and renal tubular basement membrane. Higher power view of the latter showing a central positive cell surrounded by red arrows (100 original magnification). Immunoperoxidase staining of TGF-β1, interstitium; V, vessel; G, glomerulus; LA, lymphoid aggregate.

**Right panel**

In biopsy frozen section using mAb TB21; a positively stained cell in the graft.

**Image**

A 2.5 year “nonregulated” period followed, characterized by strong positive DTH response (Fig. 3A), which was reversed by additional OKT3 therapy. Unfortunately, no PBMC were available from this time period for immunoassay analysis. K1 discontinued all immunosuppressive drugs of his own volition at year 1.5. When tested for kidney function at year 3, his serum creatinine was still in the normal range (1.3–1.4 mg/dl) and has remained so up to the present. K1 was monitored regularly for anti-donor DTH and CTL activity may resurface after a long period of quiescence (34, 35). This “metastable” feature of allotolerance, which in some cases may result in transplant rejection, creates an opportunity in longitudinal studies for comparisons to be made by the adoptive transfer of putative regulatory cells. An example of metastable alloseactivity after transplant is illustrated in Fig. 3. K1 received two doses of anti-CD3 (clone OKT3) mAb at the time of transplant followed by maintenance immunosuppression with azathioprine, prednisone, and cyclosporine. Despite these measures, an episode of biopsy-proven acute cellular rejection occurred on day 39 (Fig. 3A), which was reversed by additional OKT3 therapy. The function of the allopeptide-specific T_R cells in these patients was clearly dependent upon TGF-β1. To see whether CTLA-4 was also required, we used a blocking Ab specific for human CTLA-4. This Ab revealed a strong p37-MA-specific DTH response in patient K1 (Fig. 2B), suggesting that the epitope, which was immunodominant for the CD4+ T_R cells, is the same one recognized by the T_E cells.

The finding of the allopeptide-specific T_R cells in these patients was clearly dependent upon TGF-β1. To see whether CTLA-4 was also required, we used a blocking Ab specific for human CTLA-4. This Ab revealed a strong p37-MA-specific DTH response in patient K1 PBMC (Fig. 2C). We found a similar effect of a CTLA-4 blockade, revealing DTH to the donor Ag in the PBMC of patient L1 (Fig. 2C, right panel).

**Time course of metastable tolerance in patient K1**

Although some tolerant patients may maintain donor-specific hyporesponsiveness throughout their posttransplant course, in others anti-donor DTH and CTL activity may resurface after a long period of quiescence (34, 35). This “metastable” feature of allotolerance, which in some cases may result in transplant rejection, creates an opportunity in longitudinal studies for comparisons to be made by the adoptive transfer of putative regulatory cells. An example of metastable alloseactivity after transplant is illustrated in Fig. 3. K1 received two doses of anti-CD3 (clone OKT3) mAb at the time of transplant followed by maintenance immunosuppression with azathioprine, prednisone, and cyclosporine. Despite these measures, an episode of biopsy-proven acute cellular rejection occurred on day 39 (Fig. 3A), which was reversed by additional OKT3 therapy. Unfortunately, no PBMC were available from this time period for immunoassay analysis. K1 discontinued all immunosuppressive drugs of his own volition at year 1.5. When tested for kidney function at year 3, his serum creatinine was still in the normal range (1.3–1.4 mg/dl) and has remained so up to the present. K1 was monitored regularly for anti-donor DTH responses in peripheral blood beginning at year 4.5. DTH responses to p37-MA were consistently low over a 3-year period. However, a strongly positive DTH response to p37-MA (Fig. 3A) and HLA-B*1501 (data not shown) was detected in PBMC beginning at year 7.5. A 2.5 year “nonregulated” period followed, characterized by strong anti-donor DTH responses (Fig. 3A, gray area). A third LKP

which are indicated by arrows; center column, red staining identifies TGF-β1+ cells in same field; right column, overlay showing dual-staining cells in yellow.

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**Table III. Quantitative analysis of TGFβ1+ cells infiltrating kidney allografts of K1 and K2 number of cells per 10 tubules (mean ± SD)***

<table>
<thead>
<tr>
<th>Cell Phenotype</th>
<th>K1 (year 10.5)</th>
<th>K2 (year 18)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TB21+</td>
<td>5.0 ± 1.0</td>
<td>3.5 ± 0.5</td>
</tr>
<tr>
<td>CD4*</td>
<td>1.0 ± 0.2</td>
<td>8.5 ± 1.0</td>
</tr>
<tr>
<td>CD4*/TB21+</td>
<td>0.4 ± 0.1</td>
<td>3.5 ± 0.5</td>
</tr>
<tr>
<td>CD8*</td>
<td>0.22 ± 0.05</td>
<td>6.0 ± 1.0</td>
</tr>
<tr>
<td>CD8*/TB21+</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>CD25*</td>
<td>ND</td>
<td>1.0 ± 0.2</td>
</tr>
<tr>
<td>CD25*/TB21+</td>
<td>ND</td>
<td>0.2 ± 0.05</td>
</tr>
</tbody>
</table>

***At least 20 high power fields were counted for each determination; see Ref. 4 for details.  
**Not detected.**
ALLOPEPTIDE SPECIFIC CD25\textsuperscript{low} CD4 T\textsubscript{H} CELLS SUPPRESS DTH

To determine the surface phenotype of the TGF-\(\beta\)\textsuperscript{+} cells in the year 4.5 biopsy sample, we used dual immunofluorescence labeling. As shown in Fig. 3D, the green fluorescence signal for CD4 (top row of panels, \(\times 600\) original magnification), but not that for CD8 (lower row of panels), colocalized with a strong TGF-\(\beta\) red fluorescence signal (center column of panels), producing a bright yellow color on overlay (top right panel). The peritubular TGF-\(\beta\)\textsuperscript{+} infiltrates included some cells that costained with anti-CD25 Ab (Fig. 3D, middle row of panels), although these were less frequent than the ones that costained with anti-CD4. A quantitative analysis of cells in the tubulointerstitium was performed on the year 10.3 biopsy of patient K1 as well as the year 18 biopsy of patient K2. We used an immunoperoxidase labeling method on paraffin-embedded tissue reported previously (4) to score the graft-infiltrating cells in a blinded fashion and tabulated the results. The analysis confirmed the presence of CD4/TGF-\(\beta\) dual-stained T cells, the absence of CD8/TGF-\(\beta\) dual-stained cells, and the relative paucity or absence of CD25/TGF-\(\beta\) dual-stained T cells (Table III). Importantly, approximately one-third of the CD4\textsuperscript{+} T cells were costained for TGF-\(\beta\)\textsuperscript{1}, while CD25\textsuperscript{+} cells were either undetectable (K1) or of low frequency (K2) in the peritubular areas of both transplants.

Adaptive CD4\textsuperscript{+} T\textsubscript{H} cells express surface TGF-\(\beta\)\textsuperscript{1} after in vitro challenge

The cell surface-associated expression of TGF-\(\beta\) by CD4\textsuperscript{+} T cells in the biopsies of accepted kidney allografts suggested a way to directly visualize donor allopeptide-specific CD4\textsuperscript{+} T\textsubscript{H} cells in peripheral blood. PBMC from K1 (LKP4) and K2 were cultured with peptides for 40 h and tested for surface TGF-\(\beta\) expression by

![Image](image-url)
The percentages of CD4$^+$ T cells with TGF-$\beta_1$ surface expression in cultured LKP3 and LKP4 PBMC, corrected for background (1.0 $\pm$ 0.3% for LKP3 and 1.8 $\pm$ 1% for LKP4, cultures with medium alone). A, Numbers of IFN-$\gamma$ secreting cells, shown as spots per 3 $\times$ 10$^5$ PBMC in ELISPOT cultures. *, $p < 0.01$, comparing mean response (horizontal line) to p37-MA vs other peptides; Each symbol represents a separate determination. B, Trans-vivo DTH responses in the presence of isotype control or TGF-$\beta_1$-specific Ab. **, $p < 0.001$ vs control Ab.

Nonregulated and regulated PBMC samples contain different proportions of IFN-$\gamma$ vs TGF-$\beta_1$-inducible T cells

Although the mean fluorescence intensity of the cell surface staining for TGF-$\beta_1$ was always low, the pattern of a higher percentage of IFN-$\gamma$-inducible T cells as compared with the control self-peptide p61-C ($p < 0.01$; Fig. 4B). A similar induction of surface TGF-$\beta_1$ in the CD4$^+$ T cells of patient K2 was observed after stimulation with peptide p37-MA (data not shown). Both “background” surface TGF-$\beta_1$ induction by a self-peptide and allopeptide-inducible TGF-$\beta_1$ expression were 3- to 10-fold lower in the CD4$^+$ T cells of patient K2 as compared with those of patient K1.

To determine the CD25 phenotype of the CD4$^+$ T cells induced to express surface TGF-$\beta_1$, cultured PBMC were analyzed by flow cytometry for surface TGF-$\beta_1$ and CD25 expression. In both patients, the CD25low fraction of CD4$^+$ T cells was enriched for TGF-$\beta_1^+$ surface expression relative to the CD25high or CD25$^ <$ subsets (Fig. 4C).

flow cytometry using a chicken anti-TGF-$\beta_1$ Ab that recognizes active as well as high m.w. TGF-$\beta_1$-associated complexes in Western blots (data not shown). In a representative experiment shown in Fig. 4A, peptide p37-MA induced surface TGF-$\beta_1$ expression in 4.44% of the CD4$^+$ T cells of K1,~2.5-fold higher than that in CD4$^+$ T cells stimulated with the control self-peptide. Background staining with the isotype control Ab was $<$0.25%. Similarly, in vitro cultures of patient K2 PBMC with the donor HLA-B8-derived allopeptide p61-F induced the expression of surface TGF-$\beta_1$ in some CD4$^+$ T cells (Fig. 4A). The TGF-$\beta_1$ response was dose dependent; the highest peptide dose tested (2 mg/ml) induced a 2-fold higher mean percentage of TGF-$\beta_1^+$ CD4$^+$ T cells as compared with the control self-peptide p61-C ($p < 0.01$; Fig. 4B). A similar induction of surface TGF-$\beta_1$ in the CD4$^+$ T cells of patient K2 was observed after stimulation with peptide p37-MA (data not shown). Both “background” surface TGF-$\beta_1$ induction by a self-peptide and allopeptide-inducible TGF-$\beta_1$ expression were 3- to 10-fold lower in the CD4$^+$ T cells of patient K2 as compared with those of patient K1.

To determine the CD25 phenotype of the CD4$^+$ T cells induced to express surface TGF-$\beta_1$, cultured PBMC were analyzed by flow cytometry for surface TGF-$\beta_1$ and CD25 expression. In both patients, the CD25$^ <$ fraction of CD4$^+$ T cells was enriched for TGF-$\beta_1^+$ surface expression relative to the CD25$^ <$ or CD25$^ <$ subsets (Fig. 4C).
The reverse of this pattern was seen when allopeptide-specific Th-1 (T\textsubscript{h}) cells were analyzed using an IFN-\gamma ELISPOT assay. As shown in Fig. 5B, LKP3 cells made an IFN-\gamma response to p37-MA but not to the self-peptide p37-TE or to the irrelevant B*1501 peptide p106. The IFN-\gamma response to p37-MA by LKP4 cells, in contrast, was significantly less than that of LKP3, consistent with the DTH assay results (compare Fig. 5, B and C). Neutralizing TGF-\beta1 did not reveal any additional footpad swelling in LKP3 to p37-MA, but the same treatment of LKP4 cells revealed a moderate response. DTH responses to the control peptide, p37-TE, were negative with or without anti-Ab (Fig. 5C).

**Absence of TGF-\beta1-inducible CD4 adaptive T\textsubscript{h} cells in a case of B*1501 allosensitization**

The above results imply that the absence of TGF-\beta1-inducible adaptive T\textsubscript{h} cells can be a marker of allosensitization at the T cell level. To determine whether allosensitization at the B cell level also correlates with an absence of TGF-\beta1-inducible adaptive T\textsubscript{h} cells, we examined PBMC from K3, a HLA-DR4\textsuperscript{+} patient who received a HLA B62-mismatched renal transplant from a HLA haplotype-matched living donor along with Campath-1H (anti-CD52) induction therapy. This patient is being maintained on rapamycin monotherapy as part of an Immune Tolerance Network-sponsored tolerance trial and retains normal graft function. However, he is not currently a candidate for complete weaning off of immunosuppression due to Ab formation and C4d deposits in his kidney transplant. PBMC obtained at 1 year posttransplant from K3 responded strongly in a trans-vivo DTH assay to donor-type alloantigen HLA-B*1501 and to allopeptide p37-MA, but only weakly to control peptide p37-TE (Fig. 6A). A specific Ab to HLA-B*1501, but not to self Ag HLA-A*0201, was found in his serum by indirect luminescence assay (Fig. 6A). As expected, no linked suppression of recall DTH was detected in the presence of HLA-B*1501 (data not shown).

When the PBMC of patient K3 were cultured with HLA-B derived peptides, there was no specific induction of surface HLA-DR by LKP1 in response to p37-MA compared with p37-TE (Fig. 6B). These data are similar to the findings in LKP3 from patient K1, except that patient K3 developed a HLA-B*1501-specific anti-donor Ab, whereas patient K1 did not.

**CD4\textsuperscript{+} CD25\textsuperscript{low} T cells transfer allopeptide-specific DTH regulation**

We took advantage of the availability of nonregulated and regulated PBMC samples from the same patient (K1) to determine which CD4\textsuperscript{+} T cell subset could transfer allopeptide-specific suppression. CD4\textsuperscript{+} T cells from the first leukapheresis of patient K1 (LKP1, year 5.8) were flow-sorted into CD25 high, low, and negative subsets using the same gating strategy described in Fig. 4C. As illustrated diagrammatically in Fig. 7A, 1 x 10\textsuperscript{5} sorted cells were mixed with 9 x 10\textsuperscript{5} LKP2 (year 7.6) PBMC and allopeptide p37-MA and injected into a SCID mouse footpad. Consistent with the pattern of induced surface TGF-\beta1 expression noted above, CD4\textsuperscript{+}CD25\textsuperscript{low}, but not CD4\textsuperscript{+}CD25\textsuperscript{high} T cells were able to significantly suppress the DTH response to p37-MA (Fig. 7B). Surprisingly, CD4\textsuperscript{+}CD25\textsuperscript{high} T cells failed to suppress DTH even when added at a 3-fold higher cell dose, whereas significant DTH inhibition was obtained with as few as 5 x 10\textsuperscript{4} CD4\textsuperscript{+}CD25\textsuperscript{low} T cells (data not shown). The anti-CTLA-4 DTH response of LKP2 was only slightly reduced (p = NS) by the addition of CD4\textsuperscript{+}CD25\textsuperscript{low} T cells, confirming that the DTH inhibition effect required the presence of donor alloantigen. As a control for the isolation procedure itself, CD4\textsuperscript{+}CD25\textsuperscript{low} T cells isolated from year 7.6 PBMC (LKP2), when added to whole LKP2 cells plus p37-MA, failed to suppress the DTH response (Fig. 7C). The addition of a CTLA-4 blocking Ab also had no effect on the DTH response of LKP2 cells to p37-MA but completely reversed the inhibition of DTH by CD4\textsuperscript{+}CD25\textsuperscript{low} T cells from LKP1 (Fig. 7D).
CD4<sup>+</sup>CD25<sup>low</sup> T cells show variable CD25 expression but retain allopeptide-specific TGF-β1 responsiveness after flow sorting and short-term culture

The adoptive transfer data, coupled with the finding that mainly CD25<sup>low</sup> T cells were among the CD4<sup>+</sup>T cells that showed variable CD25 expression by immunostaining. To examine the question of CD25 expression after exposure to Ag, CD25<sup>high</sup>, CD25<sup>low</sup>, and CD25<sup>-</sup> T cells in the CD4<sup>+</sup>T cell subset were flow-sorted from a regulated blood sample (K1-LKP4). Each fraction was cultured with IL-2 and autologous APC feeder cells along with either peptide or anti-CD3 mAb. As shown in Fig. 8A, upper panels, the CD25<sup>high</sup> T cells retained stable CD25 expression in culture, and polyclonal stimulation by anti-CD3 and IL-2 induced surface TGF-β1 expression in a significant proportion of the T cells. However, there was relatively little induction of surface TGF-β1 expression by p37-MA and medium controls. The overall percentage of CD4<sup>+</sup>T cells induced to express TGF-β1 was compared in two separate experiments, and the sorted CD25<sup>high</sup> subset had the highest response to anti-CD3 stimulation while the sorted CD25<sup>low</sup> subset had the highest response to allopeptide p37 stimulation (p < 0.01, CD25<sup>low</sup> vs CD25<sup>high</sup>; Fig. 8B).

TGF-β1-expressing CD4<sup>+</sup>T<sub>R</sub> cells are FoxP3<sup>-</sup> and are distributed differently from FoxP3<sup>+</sup>T<sub>R</sub> cells in the kidney allograft

To address the possible relationship between adaptive and FoxP3<sup>-</sup>T<sub>R</sub> in kidney allograft tolerance, we first compared expression of...
FoxP3 and TGF-β1 cells in the peripheral blood and TGF-β1 cells in the interstitium of kidney allografts are FoxP3⁺. A, K1 LKP4 were cultured with p37-MA and stained for surface CD25/TGF-β1 and intracellular FoxP3. Cells shown here are gated for CD4⁺ T cells and are representative of four independent experiments. B, Allograft renal biopsies from patients K1 (top panels) and K2 (bottom panels) were immunolabeled by immunoperoxidase for TGF-β1 (purple) and FoxP3 (brown). TGF-β1/FoxP3⁺ cells were found in the interstitium of both biopsies (left panels) whereas TGF-β1/FoxP3⁻ cells were seen primarily in lymphoid aggregates (right panels). Right bottom insets are the cells indicated by arrow at low power. C, Highlights a cell that is double positive for CD25 (purple) and FoxP3 (brown) in the lymphoid aggregate of the kidney biopsy of patient K2. No CD25⁻FoxP3⁻ cells were seen in the renal interstitium outside of the lymphoid aggregates. D, A splenocyte that is double positive for TGF-β1 (purple) and FoxP3 (brown) in normal human spleen.

Discussion

The data suggests that two distinct classes of human CD4⁺ T regulatory cells participate in tolerance to a kidney transplant. One class consists of Ag-specific, adaptive Tₘ cells induced by donor HLA-B allopeptides. These Tₘ cells expressed surface TGF-β1 upon Ag stimulation and circulated in the CD4⁺CD25low fraction of PBMC. Phenotypically similar (CD4⁺TGF-β1⁻CD25low⁻) cells were found in the allograft, mainly localized to the tubulointerstitium, where they have been found previously in rhesus monkey kidney transplants during tolerance (4). As in the monkey model, such CD4⁺ adaptive Tₘ cells were absent from the peripheral blood of a patient who failed to become tolerant following leukocyte-depleting Ab therapy, developing instead a strong anti-donor HLA B-specific Ab and DTH response (Fig. 6). The other class consists of CD4⁺FoxP3⁺ natural Tₘ cells, which were found in lymphoid aggregates within the accepted allograft and circulated mainly in the CD4⁺CD25high fraction of PBMC. In normal subjects, this same fraction has been found to suppress the proliferation of CD4⁺CD25⁻ T cells in an Ag nonspecific manner (13). Human CD4⁺CD25high T cells can also be induced to express surface TGF-β1 in vitro by polyclonal activation with anti-CD3 and IL-2 (Fig. 8) (38). We have recently found that, once activated in this manner, CD4⁺CD25high T cells but not CD25⁻ T cells suppress a trans-vivo DTH response by fresh PBMC to a recall Ag in the SCID mouse footpad; this suppression was TGF-β dependent. However, CD4⁺CD25low T cells did not suppress any DTH response unless activated via anti-CD3 and anti-CD28 (Q. Xu, E. Jankowska-Gan, and W. Burlington, unpublished observations). The transfer of nonactivated CD4⁺CD25high T cells could not restore a regulated DTH response to allopeptide in PBMC lacking such regulation. Instead, it was the CD4⁺CD25low T cells present in regulated PBMC samples that were able to transfer suppression of allopeptide response efficiently and specifically (Fig. 7). These data are consistent with findings in the mouse suggesting that the restoration of specific tolerance to pancreatic islet autoantigens in vivo requires CD4⁺CD25low as well as CD4⁺CD25high Tₘ cells (8) and that dominant tolerance may in some cases suppress the functions (e.g., cytokine production, DTH) but not the expansion of Tₘ cells (6, 28, 39).

The DTH transfer data using cells collected from patient K1 indicated that only the CD25low fraction of CD4 T cells contained functional allopeptide-specific Tₘ cells. However, we cannot rule out the possibility that the CD4⁺FoxP3⁺CD25high fraction of PBMC might also include some adaptive Tₘ cells. Indeed, a minor population of CD4⁺CD25high T cells was induced to express surface TGF-β1 by allopeptide stimulation (Fig. 7B). Although in vitro derived human adaptive Tₘ cells that coexpress FoxP3 and TGF-β1 is double positive for TGF-β1 in the renal interstitium outside of the lymphoid aggregates. Few surface TGF-β1 FoxP3 and TGF-β1 are present in normal human spleen.
high levels of CD25 have been reported (15), whether or not FoxP3 expression that has been induced in conventional human CD4 T cells is stable in vivo remains controversial (16). It is noteworthy that FoxP3+ T<sub>R</sub> cells tend to be lymph node homing (40). In contrast, surface TGF-β1+FoxP3<sup>new</sup> T cells in the renal biopsy samples of patients K1 and K2 were localized to the peritubular interstitium, consistent with a tissue-homing T cell phenotype. The function of lymphoid aggregates commonly observed in accepted kidney transplants has long remained a mystery (for a review, see Ref. 37). The finding that the lymphoid aggregates in the allografts of patients K1 and K2 were enriched in FoxP3+ T<sub>R</sub> cells (and recently confirmed in the rhesus monkey kidney transplant tolerance model; J. R. Torrecilla, unpublished observations) suggests that the aggregates themselves may be tertiary lymphoid structures that retain natural FoxP3+ T<sub>R</sub> cells but allow the adaptive T<sub>R</sub>/<sub>E</sub> suppressive cells to pass through to the tubulointerstitium.

Unlike the CD25<sup>high</sup>/FoxP3+ T<sub>R</sub> cells, which retained high CD25 expression in vitro (Fig. 8) and in vivo (Fig. 9C), CD25<sup>high</sup>/CD4<sup>+</sup> T cells appear to be heterogeneous. Flow-sorted human CD4+CD25<sup>high</sup> T cells gave rise to both CD25<sup>high</sup> and CD25<sup>−</sup> T cells when cultured for 36 h.; in the presence of the p37MA allopeptide, the derivative CD25<sup>high</sup>/FoxP3<sup>−</sup> populations each contained cells that expressed surface TGF-β1 (Fig. 8). Similarly, surface TGF-β1+ T<sub>R</sub> cells in the graft were heterogeneous in CD25 expression. Viguier et al. (3) reported that both CD25<sup>high</sup>/FoxP3<sup>+</sup> and CD25<sup>−</sup>/FoxP3<sup>−</sup> T<sub>R</sub> cells were present in metastatic lymph nodes of patients with advanced malignant melanoma; interestingly, the majority of TGF-β1 production came from the latter subset. The relative importance of each class of T<sub>R</sub> cells in maintaining tolerance is unclear. It has recently been reported that FoxP3 mRNA is more highly expressed in the urine sediment cells of patients undergoing a reversible, as opposed to irreversible, acute rejection (41). This finding is consistent with our observation of the CD25<sup>high</sup>/FoxP3<sup>−</sup> class of T<sub>R</sub> cells in biopsy samples from two tolerant patients, one of whom (K1) developed renal allostolerance after the reversal of an acute rejection episode.

The T<sub>R</sub>/T<sub>E</sub> equilibrium model predicts that the disappearance or elimination of adaptive T<sub>R</sub> cells (2, 4) or interference with their function (42) will lead to the re-emergence of T<sub>R</sub> response and the breakdown of tolerance. However, unlike a patient who developed anti-donor DTH responsiveness at year 9.0 and rejected his maternal kidney transplant at year 10 (35), and unlike the monkeys that lost their renal allografts to rejection shortly after regaining a strong peripheral anti-donor DTH response (4), patient K1 did not lose his graft after the restoration of anti-donor DTH response at year 7.5 posttransplant. There are several possible explanations for this, none of which fits with a simple T<sub>R</sub>/T<sub>E</sub> equilibrium model of peripheral tolerance. One explanation is that because the graft donor was closely DR and DQ matched, the B lymphocytes of K1 would be unable to form class II donor-specific Ab even in the presence of adequate T cell help. Indeed, no anti-HLA-class I or II Abs were detected, either by sensitive flow-heads or Luminex-based assays, in serum samples collected between year 5 and year 10 posttransplant (J.-H. Lee and W. Burlingham, unpublished observations). However, HLA-class II matching alone is not a satisfactory explanation. Many DR-matched kidney transplants undergo rejection, while some fully DR-mismatched grafts can be accepted (patient K2 being a case in point). Also, patient K3 was humorally sensitized not only to donor HLA-B*1501 (Fig. 6A) but also to a donor HLA-DR13 Ag (S. Knechtle, unpublished observations). Although this patient is clearly not tolerant, he continues to have good renal function on rapamycin monotherapy despite anti-HLA Ab formation. A second possible answer is that because patient K1 has a low producer IFN-γ and TNF-α genotype (43), his T<sub>E</sub> cells would be susceptible to inhibition even by low levels of TGF-β1 (44). A third possibility is that despite their disappearance from the blood, TGF-β1-inducible CD4<sup>+</sup> T<sub>R</sub> cells were still able to localize to the allograft while IFN-γ-producing T<sub>E</sub> cells could not. We did not risk testing this idea because it would have entailed a biopsy of the kidney and a concomitant risk of infection at a time when systemic adaptive immunity was strongest. Innate immune mechanisms are involved in the mobilization of T<sub>E</sub> cells from the blood to the graft that precipitates transplant rejection (45); thus, even when the circulating component of adaptive immunity is unbalanced in favor of T<sub>E</sub> cells, allograft rejection may still be prevented in the absence of local secondary signals provided through innate immune pathways.

The adaptive T<sub>R</sub> cells identified in this study recognized allopeptide epitopes. The rules that govern this recognition appear to be the same as those involved in determining specificity of conventional T<sub>E</sub> cells. Thus, for example, HLA-B<sup>*1501</sup>-specific CD4<sup>+</sup> T<sub>R</sub> and T<sub>E</sub> cells were present in patients K1 and L1, yet different HLA-DR Ags in patient K1 (DR4, 6) vs L1 (DR15, −) were associated with different patterns of T<sub>R</sub> and T<sub>E</sub> allopeptide specificity. Surprisingly, p37-MA was not only a dominant allopeptide for patients K1 and K3 but also for K2, even though K2 was mismatched for a different p37-MA-containing HLA-B allele (B*5701 vs B*1501) and expressed different HLA-DR/DQ alleles. The fact that K3, a DR4/DR15 heterozygous patient, responded to p37-MA whereas L1, who was homozygous for DR15, did not suggests that either the DR4 itself or the DR4-linked DQ3 Ag provides an HLA restriction element for indirect pathway recognition of this allopeptide. The class II restriction element for p37-MA in patient K2 is less clear. A degree of promiscuity in peptide binding and recognition was previously suggested for CD4 indirect pathway T cells cloned from a transplant nephrectomy (46), one of which was inducible for surface TGF-β1 and had the functional characteristics of an adaptive T<sub>R</sub> cell (47).

The numbers of T<sub>E</sub> cells responding to a single allopeptide appeared to be higher in patient K1 (LKP4) than in K2 when calculated by subtraction of the “self” HLA-B peptide-induced background response: 1–3% of CD4<sup>+</sup> T cells surface TGF-β1 in K1 as compared with 0.2–0.4% in K2. When calculated as a multiple of the background response to self-peptide, the relative number of CD4<sup>+</sup>/TGF-β1+ responder cells in both patients fell into the same range: 2–3 times background. T<sub>E</sub> cell frequencies to a given allopeptide could be calculated more accurately based on an IFN-γ ELISPOT assay. For example, T<sub>E</sub> cells responding to p37-MA in K1 LKP3 cells were ~0.03% of CD4<sup>+</sup> T cells (Fig. 4). This number is well within the range of the values obtained by an IFN-γ ELISPOT assay of indirect pathway CD4<sup>+</sup> T cells responding to HLA-DR-derived allopeptides in patients with DR-mismatched renal allografts (48).

Our data suggest a key role of CTLA-4 in the function of CD4<sup>+</sup> adaptive T<sub>R</sub> cells. The reversal by CTLA-4 blocking Abs of DTH suppression in the CD25<sup>low</sup>/FoxP3<sup>+</sup> cell transfer assay (Fig. 7D) suggests that CTLA-4 is critical for interaction of the T<sub>R</sub> cell with the APC, as has been previously suggested for the CD4<sup>+</sup>/CD25<sup>+</sup> natural T<sub>R</sub> (49, 50). In preliminary in vitro studies, we have found that the blockade of CTLA-4 also prevents the induction of surface TGF-β1 in both polyclonally stimulated natural T<sub>R</sub> cells and in adaptive T<sub>R</sub> cells responding to donor allopeptide (Q. Xu and W. Burlingham, unpublished observations), suggesting that CTLA-4 is involved in the induction of TGF-β1 as has been previously suggested (51).

In summary, an analysis of two cases of tolerance to HLA-mismatched organ allografts supports the hypothesis that peripheral tolerance involves a balance between CD4<sup>+</sup>CD25<sup>low</sup> adaptive
T₉ cells and CD4⁺ T₉ cells specific for the same donor-derived class I allopeptides. The adaptive T₉ cells identified in this study were distinct in both function and intragraft localization from CD4⁺ CD25 high Foxp3⁺ T cells. The finding of distinct subsets of CD4⁺ Foxp3⁻ adaptive T₉ cells vs CD25 high Foxp3⁺ T₉ cells and the fortuitous observation of a metastable form of human transplant tolerance will need to be confirmed in a larger series of tolerant patients. Coordinated efforts to find and study these rare individuals are currently underway in Europe and North America (52).

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The authors have no financial conflict of interest.

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13. References


