Frequency of Circulating Tregs with Demethylated FOXP3 Intron 1 in Melanoma Patients Receiving Tumor Vaccines and Potentially Treg-Depleting Agents

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Abstract

**Purpose:** Regulatory T cells (Tregs) are thought to inhibit antitumor immune responses, and their depletion could therefore have a synergistic effect with therapeutic cancer vaccines. We investigated the impact of three medications on blood Treg frequency in vaccinated cancer patients.

**Experimental Design:** To date, the most specific marker for human Tregs is demethylation in the DNA that encodes the transcription factor FOXP3. Thus, we used a FOXP3 methylation-specific quantitative PCR assay (MS-qPCR) to measure Treg frequencies in the peripheral blood mononuclear cells (PBMCs) of melanoma patients. The patients participated in three clinical trials that combined tumor vaccines with potential Treg-depleting agents: low-dose cyclophosphamide, anti-CD25 monoclonal antibody daclizumab, and the IL-2/diphtheria toxin fusion protein denileukin difitox.

**Results:** In the nine control patients, blood Treg frequencies varied over time; there was a 46% reduction in one patient. In treated patients, a more than 2-fold decrease in Tregs was observed in one out of 11 patients receiving cyclophosphamide and in four out of 13 receiving daclizumab, but there was no such Treg decrease in any of the six patients who received denileukin difitox. As a positive control, a more than 2-fold increase in blood Tregs was detected in four out of nine patients who were treated with interleukin-2.

**Conclusions:** We used a MS-qPCR method that detects Tregs but not other activated T lymphocytes; however, none of the Treg-depleting strategies that we tested led, in the majority of patients, to a conservative 50% reduction in blood Tregs. *Clin Cancer Res;* 17(4); 1–8. ©2010 AACR.

Introduction

Antigens on human tumor cells that are recognized by T lymphocytes can be used to develop tumor-specific active immunotherapy. Several small clinical trials have investigated the therapeutic and immunologic efficacy of vaccinating advanced-stage cancer patients with defined tumor antigens. In previously published studies of patients with metastatic melanoma, about 5% of vaccinated patients showed a complete or partial clinical response, whereas an additional 10% displayed some evidence of tumor regression without clear clinical benefit (1, 2). Because most antitumor vaccination modalities are not associated with serious adverse effects, therapeutic vaccination with defined antigens remains a promising approach, provided that its clinical efficacy increases substantially.

Improvements in clinical efficacy could be made by vaccinating earlier, at a stage in which there is minimal residual disease after treatment of the primary tumor; from the use of improved vaccines that induce stronger and broader T cell responses; or from combining vaccines with immunomodulation. Indeed, detailed studies of T cell responses in melanoma patients suggest that the major factor limiting the efficacy of cancer vaccines may be an immunosuppressive environment within tumors (1, 3–5). Candidate immunosuppressive mechanisms include production by tumor cells of soluble immunosuppressive molecules such as TGF-β, galectins, or indoleamine 2,3-dioxygenase (IDO), or suppressive cells such as myeloid-derived suppressive cells or regulatory T cells (Tregs; ref. 1). Tregs are a subset of CD4⁺ CD25⁺ T cells that specialize in the inhibition of immune responses (6). Their development and function depends on the transcription factor FOXP3, as illustrated by the severe Treg deficiency and autoimmune disease observed in patients with FOXP3...
Regulatory T cells (Tregs) are thought to inhibit antitumor immune responses. Agents that deplete Tregs in cancer patients could therefore improve the efficacy of therapeutic cancer vaccines. We compared the efficiency of 3 potentially Treg-depleting agents administered to vaccinated melanoma patients by measuring blood Treg frequencies with an epigenetic assay that is not confounded by the presence of activated non-Tregs. Our results show that neither daclizumab, nor low-dose cyclophosphamide or denileukin difitox induced a more than 50% decrease in blood Tregs in a majority of the patients. This study indicates that different therapeutic strategies are required to further evaluate whether Treg depletion can improve cancer vaccine response.

Translational Relevance

Regulatory T cells (Tregs) are thought to inhibit antitumor immune responses. Agents that deplete Tregs in cancer patients could therefore improve the efficacy of therapeutic cancer vaccines. We compared the efficiency of 3 potentially Treg-depleting agents administered to vaccinated melanoma patients by measuring blood Treg frequencies with an epigenetic assay that is not confounded by the presence of activated non-Tregs. Our results show that neither daclizumab, nor low-dose cyclophosphamide or denileukin difitox induced a more than 50% decrease in blood Tregs in a majority of the patients. This study indicates that different therapeutic strategies are required to further evaluate whether Treg depletion can improve cancer vaccine response.
the peptide pulse. Batches of 12 million peptide loaded-DC per MHC class I peptide were injected intracutaneously on days 0, 14, 42 and 70. For the first vaccination only, a single additional batch of DC was pulsed with KLH (10 μg/ml). On days −3, −2, and −1 before the first DC injection, 18 patients received infusions of denileukin diftitox (Ontak, 5 μg/kg, i.v.). Analyses of clinical and immune responses will be described elsewhere.² PBMC samples from 6 patients were available for this retrospective study.

**Vaccination with peptide pulsed DCs combined to IL-2.** Patients with AJCC stage III melanoma were enrolled in this study on the basis of the same additional inclusion criteria described for the DC + daciluzumab study. Vaccines consisted of autologous mature DCs pulsed with gp100 and tyrosinase peptides and KLH injected into an inguinal clinically tumor-free lymph node under ultrasound guidance. A total of 22 patients received 1 cycle of 4 vaccinations every 2 weeks. In addition to the vaccines, 10 of the patients received daily low-dose IL-2 (9 MIU, s.c.) during 1 week. Analyses of clinical and immune responses will be described elsewhere.³

For all studies, approval from the local regulatory committee was obtained and patients gave written informed consent prior to inclusion.

**MS-qPCR for FOXP3i1**

Genomic DNA (gDNA) was prepared from frozen pellets containing 4 × 10⁵ to 10⁶ total PBMCs with the PureLink Genomic DNA Mini Kit (Invitrogen). One to 2 μg of EcoRI-digested gDNA was treated with sodium bisulfite using the MethylCode Bisulfite Conversion kit (Invitrogen). Real-time PCR amplification of methylated and demethylated FOXP3i1 sequences were performed on 30 to 125 ng of bisulfite converted DNA in a final volume of 25 μL with 0.6 U of HotGoldStar DNA polymerase (Eurogentec), 300 nM of each primer, 100 nM of probe, 200 μM of dNTP, and 5 mM of MgCl₂ in an ABI 7300 Real Time PCR system (Applied Biosystems) under standard conditions: 94°C for 10 minutes, 45 cycles of 94°C for 15 seconds and 64°C for 1 minute. Sequences of primers and probes are indicated in Supplemental Table S1, and their activity, but not in others (11). In this study, we used the Vaccine as the 4 patients in the "DC vaccine only" arm of the "DC vaccine + IL-2" trial. Mean variations in the other groups were compared to mean variation in the control group by performing a Student’s t-test (P values are indicated in Supplemental Table S2).

**Results and Discussion**

**FOXP3i1 MS-qPCR assay to measure frequency of human Tregs**

We previously developed a MS-qPCR assay to quantify cells with demethylated FOXP3i1, and used it on a large panel of human T cell clones to show that demethylated FOXP3i1 is found in CD4+ Treg clones with suppressive activity, but not in others (11). In this study, we used the assay on blood mononuclear cells. Cells with demethylated FOXP3i1 were enriched in the CD4+ subset, and present in the other subsets as a proportion of the contaminating CD4+ lymphocytes (Fig. 1A). These results are in line with those of Wieczorek and colleagues, who showed that demethylated FOXP3i1 sequences are found only in the CD4+ CD25hi fraction (14). It is important to note that the frequencies of cells with demethylated FOXP3i1 were not increased in purified CD4+ CD25hi cells that were activated in vitro, even in the presence of TGF-β (Fig. 1B). This is in sharp contrast with the proportion of FOXP3-expressing cells, which increased after activation, especially in the presence of TGF-β (Fig. 1B). In human CD4+ T cells, this transient FOXP3 expression after activation with TGF-β is not associated with the acquisition of suppressive functions (10, 29). Taken together, these results confirmed that detecting demethylated FOXP3i1 by MS-qPCR is a reliable method for measuring Tregs in human blood.

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²Schuler-Thurner et al., manuscript in preparation.
³Lesterhuis et al., manuscript in preparation.
Frequency of Tregs in metastatic melanoma patients not receiving Treg-depleting agents

In this retrospective study, we measured the blood Tregs of patients with melanoma who were participating in 3 independent clinical trials that combined tumor vaccines with potential Treg-depleting agents, and in a fourth trial combining vaccines with IL-2. The numbers of included patients were small, and multiple samples were available for only 9 patients who received neither a Treg-depleting agent nor IL-2. In these control patients, Treg frequency varied over time, with a maximum increase of 260% and decrease of 46% (Supplemental Table S2). We therefore chose a conservative reduction of 50% to qualify patients as responders to the Treg-depleting agents.

Frequency of Tregs in patients receiving tumor vaccines and a Treg-depleting agent

In the first trial, 15 patients with stage IV melanoma received daclizumab (0.5 mg/kg, intravenous [i.v.]) 4 or 8 days before vaccination with mature dendritic cells (DCs) pulsed with keyhole limpet hemocyanin and the melanoma-associated peptides gp100154–167, gp100280–288, and tyrosinase369–376 (26). Daclizumab caused a rapid and complete depletion of all blood cells expressing high levels of CD25 (including CD4+CD25+FOXP3+CD127− cells), but did not affect FOXP3+ cells expressing low levels or no CD25 (26). Because in humans, expression of CD25 or FOXP3 protein expression. (B) CD4+CD25+ cells purified from PBMCs with magnetic beads were analyzed by MS-qPCR and by FACS, either 

Table 1. MS-qPCR assay to quantify human Tregs: (A) The indicated subsets of PBMCs were purified with magnetic beads. Total PBMCs and purified subsets were analyzed by MS-qPCR to quantify cells with demethylated FOXP3, and by flow cytometry for surface CD3 and CD4 and intracellular FOXP3 protein expression. (B) CD4+CD25+ cells purified from PBMCs with magnetic beads were analyzed by MS-qPCR and by FACS, either ex vivo or after 5 days of in vitro stimulation with anti-CD3 and anti-CD28 antibodies in the presence of IL-2 ± TGF-β, as indicated.

Figure 1. Ex vivo analysis of total PBMCs and purified subsets

<table>
<thead>
<tr>
<th>Cells with demethylated FOXP3</th>
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<tbody>
<tr>
<td>CD5+CD4+ lymphocytes</td>
<td>50.2%</td>
</tr>
<tr>
<td>CD4+FOXP3+ cells</td>
<td>5.4%</td>
</tr>
<tr>
<td>CD8+ cells</td>
<td>0.8%</td>
</tr>
<tr>
<td>CD19+ cells</td>
<td>0.1%</td>
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<tr>
<td>CD14+ cells</td>
<td>0.1%</td>
</tr>
<tr>
<td>CD56+ cells</td>
<td>0.4%</td>
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Figure 2. CD4+CD25+ purified cells analysed ex vivo and after in vitro culture

<table>
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<th>Cytokines in culture</th>
<th>Ex vivo</th>
<th>MS-qPCR</th>
<th>FACS</th>
</tr>
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<tr>
<td>IL-2</td>
<td>n.a.</td>
<td>4.2%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Day 5 postactivation with plastic coated &gt;CD3 and soluble &gt;CD28</td>
<td>IL-2 + TGF-β</td>
<td>1.9%</td>
<td>98%</td>
</tr>
<tr>
<td>IL-2 + TGF-β</td>
<td>2.4%</td>
<td>98%</td>
<td>66.3%</td>
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Figure 3. MS-qPCR and FACS analysis of total PBMCs and purified subsets

<table>
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<th>Cells with demethylated FOXP3</th>
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<tr>
<td>CD56+ cells</td>
<td>0.4%</td>
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Figure 4. Frequency of Tregs in patients receiving tumor vaccine and IL-2

IL-2 therapy can increase Tregs, as suggested by increases in FOXP3+ or CD25+CD4+ T cells in cancer patients receiving IL-2 (30–33). However, firm conclusions cannot be drawn from these studies, because FOXP3 and CD25...
Figure 2. Treg frequencies in patients receiving tumor vaccines combined to potentially Treg-depleting agents. PBMC samples were analyzed by MS-qPCR for FOXP3i1. Each line represents Treg frequencies in 1 patient. (A) Samples collected from patients who received daclizumab injections before vaccination with KLH and melanoma peptide-pulsed DCs (injection time points indicated by arrows below the graphs). Patients with more than 2-fold Treg decrease compared to baseline levels are indicated by red lines. (B) Samples collected from patients who received injections of low dose cyclophosphamide, melanoma peptides emulsified in Montanide and IL-2 (injection time points indicated by arrows below the graphs). Patients with more than 2-fold Treg decrease compared to prevaccine levels (day 7) or with more than 2-fold increase compared to pre-IL-2 levels (day 56) are indicated by red lines. (C) Samples collected from patients who received denileukin diftitox infusions 3, 2, and 1 days prior to vaccination with melanoma peptide pulsed DCs (injection time points indicated by arrows below the graphs).
expression is induced in non-Treg T cells by antigenic activation or by IL-2 itself. Wiezcorek and colleagues recently reported increases in the frequency of Tregs with demethylated FOXP3\textsuperscript{i1} in melanoma patients treated with IL-2\textsuperscript{14}. Thus, the 2-fold Treg increase that we observed after IL-2 administration in half of the patients who received cyclophosphamide combined with a vaccine is in line with this previous observation (Fig. 2B). We wished to confirm this effect of IL-2, and to compare the frequencies of Tregs with demethylated FOXP3\textsuperscript{i1} with those of FOXP3\textsuperscript{+}CD4\textsuperscript{+} cells. To this end, we used both MS-qPCR and flow cytometry on PBMCs from patients in a fourth clinical trial, who received a vaccine with or without IL-2.\textsuperscript{6} Stage III melanoma patients were injected 4 times at biweekly intervals with DCs pulsed with gp100 and tyr-

\textsuperscript{6}Lesterhuis et al., manuscript in preparation.
osinase peptides and KLH, as in the daclizumab trial. Two days after each injection, some patients received low-dose IL-2 (9 MIU, s.c. daily for 1 week). Using MS-qPCR for FOXP3i1, the mean Treg frequencies were shown to increase 3-fold after IL-2 was administered (Fig. 3A, left panel). Individual analyses showed this increase in all but 1 out of the 6 patients receiving IL-2, and in none out of the 4 patients who received the vaccine alone (Fig. 3B). Treg increases were detectable 3 weeks after the first IL-2 injection, and persisted for at least 3 weeks after the last injection. Using flow cytometry, we also found increases in the frequencies of CD4+ cells expressing FOXP3 (Fig. 3A, middle panel, and Fig. 3B). The increases observed with MS-qPCR were slightly higher than those observed with flow cytometry, notably for patient 4.7 (Fig. 3B). We have no definitive explanation for these differences. The mean frequencies of total CD4+ cell did not vary between the different time points or groups of patients (Fig. 3A, right panel). The results clearly confirmed that an increase in blood Tregs occurred after administration of IL-2, and provided a positive control for our FOXP3i1 MS-qPCR method.

In conclusion, our quantification of Tregs using a method that is not confounded by the presence of activated CD4+ T cells indicated that none of the Treg-depleting regimens tested here reduced the frequency of blood Tregs efficiently (i.e., by a factor of 2 or more) in most of the treated patients. However, of the 3 regimens tested, daclizumab was the most promising. Unfortunately, its administration had no significant effect on the progression-free survival of the vaccinated melanoma patients included in the trial (26). Furthermore, it appeared to blunt the antivaccine T cell response, because functional antivaccine CD8+ T cells were not detected in any of the daclizumab-treated patients. This effect is probably a consequence of the transient expression of CD25 on the surface of all activated T cells, and of the persistence of the deleting anti-CD25 antibody in the serum for at least 1 month (26). At present, it is unclear whether it will be possible to deplete Tregs with anti-CD25 reagents while sparing activated T cells. New strategies, possibly based on a better understanding of human Treg immunosuppressive mechanisms, are required to assess the impact of depletion or functional invalidation of these cells during cancer immunotherapy.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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