Regulatory T Cells Are Reduced During Anti-CD25 Antibody Treatment of Multiple Sclerosis

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**Objective:** Maintenance therapy with anti-CD25 antibody has emerged as a potentially useful treatment for multiple sclerosis (MS). Constitutive CD25 expression on CD4+CD25+ regulatory T cells (Treg) suggests that anti-CD25 antibody treatment may potentially target a subset of T cells that exhibit immune suppressive properties. We examined changes to CD4+CD25+ Treg in patients with MS receiving maintenance anti-CD25 monoclonal antibody treatment to determine the effect of treatment on Treg and, consequently, on immunological tolerance.

**Design:** Peripheral blood and cerebrospinal fluid samples obtained from a before-and-after trial of anti-CD25 antibody monotherapy were examined to compare baseline and treatment differences in CD4+CD25+ Treg.

**Subjects:** A total of 15 subjects with MS. One subject was withdrawn owing to an adverse effect.

**Results:** Sustained reduction of the frequency of CD4+CD25+ Treg was observed during treatment. Anti-CD25 antibody treatment led to evidence of impaired in vivo Treg proliferation and impaired ex vivo Treg suppression. Inflammatory MS activity was substantially reduced with treatment despite reduction of circulating Treg, and there was no correlation between changes in the frequency of Treg and changes in brain inflammatory activity. However, new-onset inflammatory disease, notably dermatitis, was also observed in a number of subjects during treatment.

**Conclusion:** The reduction in Treg did not negatively affect maintenance of central nervous system tolerance during anti-CD25 antibody treatment. The incidence of new-onset inflammatory disease outside of the central nervous system in a subset of patients, however, warrants further studies to examine the possibility of compartmental differences in the capacity to maintain tolerance in the setting of reduced CD4+CD25+ Treg.


**The anti-CD25 monoclonal antibody daclizumab targets the α subunit of the high-affinity interleukin (IL)-2 cytokine receptor complex.** The upregulation of CD25 following T cell activation and the subsequent IL-2 signaling constitutes a key event in T cell clonal expansion and differentiation. Abnormalities of the IL-2–CD25 cytokine pathway have been reported in a number of immune-mediated diseases including multiple sclerosis (MS) and suggest that CD25 is a potential target for MS immunotherapy. Increased soluble CD25 levels and abnormally high IL-2 responsiveness of autoreactive T cells in subjects with MS implicate an aberrant IL-2/CD25 circuit in the pathogenesis of MS, and constitute the rationale for anti-CD25 antibody treatment to modulate IL-2 signaling in MS. A number of clinical studies are beginning to demonstrate the immunomodulatory effect of the anti-CD25 monoclonal antibody daclizumab in subjects with MS. Experimental evidence of the past decade has made increasingly clear that a subset of CD25-expressing CD4+ T cells demonstrate suppressive or regulatory properties and contribute to the maintenance of immunological self-tolerance by their inhibitory influence on autoreactive T cells. These CD4+CD25+ regulatory T cells (Treg) are distinguished from conventional activated T cells by constitutive high expression of CD25 and by the expression of Treg lineage specification factor forkhead box P3 (Foxp3). Conventional activated T cells, by contrast, express intermediate levels of CD25 and lack Foxp3. Whereas conventional activated T cells coordinate and amplify immune responses, CD4+CD25+ Treg actively suppress immune responses, including those involved in autoimmunity. The development of multiorgan inflammatory disease following Treg depletion indicates that CD4+CD25+ Treg make a critical contribution to the maintenance of immunologic self-tolerance. The loss or dysfunction of CD4+CD25+ Treg...
has been implicated in the pathogenesis of a growing number of disorders including systemic lupus erythematosus, psoriasis, aplastic anemia, and MS, suggesting a potentially broad relevance with respect to human autoimmune diseases.

The shared expression of CD25 on conventional activated T cells and CD4^+CD25^+ Treg suggest that both are potentially targeted by anti-CD25 antibody. Based on the knowledge that CD4^+CD25^+ Treg contribute to maintenance of tolerance, an inhibitory effect on Treg could potentially exacerbate existing inflammatory disease or unmask underlying predilection for new inflammatory disease. We therefore examined the changes to the CD4^+CD25^+ T cell subsets in subjects with MS undergoing anti-CD25 antibody treatment. In particular, we asked what effect an antihuman CD25 antibody has on CD4^+CD25^+ Treg, whether changes to CD4^+CD25^+ Treg affected the immunomodulatory effect of treatment, and whether changes to CD4^+CD25^+ Treg affected maintenance of overall immunological tolerance.

**METHODS**

**SAMPLES**

Subjects with MS were enrolled in an open-label trial of anti-CD25 antibody (daclizumab). Subjects were free of immunomodulatory therapy for 24 weeks prior to enrollment and received intravenous infusion of daclizumab monotherapy (1 mg/kg) every 4 weeks for 54 weeks. Peripheral blood was obtained at baseline and during treatment. Cerebrospinal fluid was obtained intravenous infusion of daclizumab monotherapy. Puriﬁed CD4^+CD25^+ Treg were sorted by FACS and used for Treg coculture suppression assay as described above.

**FLOW CYTOMETRY**

The following antibodies were used according to manufacturer’s instructions: CD3, CD4, CD8, CD25 (M-A251), CD56, CD127, IL-2, Ki67, and p53 (signal transduction and activator of transcription 5) antibodies were obtained from BD Biosciences (San Jose, California). The Foxp3 phycocerythrin (PE) or allophycocyanin antibodies were obtained from eBioscience (San Diego, California). The CD25 (Anti-Tac) fluorochrome isothiocyanate conjugate was from Immunotech (Westbrook, Maine). The CD25 (7G7) PE was from Ancell (Bayport, Minnesota). The FACS analysis of surface markers were performed on erythrocyte-lysed washed whole blood samples. The PBMC were used for all other analyses. Green Dead Stain (In vitrogen, Carlsbad, California) was used for live or dead cell discrimination with Foxp3 staining. Flow cytometric data was acquired on FACS Calibur (BD Biosciences) and analyzed on FlowJo (TreeStar, Ashland, Oregon).

**BASELINE CD4^+CD25^+ TREG CHARACTERISTICS IN SUBJECTS WITH MS**

To establish pretreatment characteristics of CD4^+CD25^+ Treg in this cohort of subjects with MS, Treg suppression was measured by an in vitro Treg coculture assay (Figure 1A). Most subjects in this cohort demonstrated baseline Treg suppression within the range for healthy donors (P = .27) (Figure 1B). Likewise, the frequency of circulating CD4^+ Foxp3^+ Treg in this cohort of subjects with MS did not differ significantly at baseline compared with that of age-, sex-, and race-matched healthy donors.
REGULATORY T CELLS DURING ANTI-CD25 ANTIBODY TREATMENT

Antibody saturation was monitored during the course of anti-CD25 antibody treatment by flow cytometry using 2 fluorochrome-labeled antibodies (anti-Tac and 7G7) that bind noncompeting epitopes on CD25. Complete antibody saturation of CD25, demonstrated by the absence of fluorochrome-labeled anti-Tac binding, was maintained during the course of treatment (Figure 2A, anti-Tac). Whereas reduction in the mean total CD25 expression on lymphocytes was less pronounced (13%) but nevertheless statistically significant (P < .001) (Figure 2A, 7G7). Examination of cerebrospinal fluid demonstrated complete antibody saturation of CD25 on cerebrospinal fluid lymphocytes and a 20% decline in mean total CD25 expression during treatment (P = .04) (Figure 2B).

Signaling of IL-2 was inhibited by anti-CD25 antibody treatment. STAT5 phosphorylation, which mediates downstream IL-2 signaling, was used as a marker of IL-2 signaling. Lymphocytes obtained during treatment demonstrated nearly complete absence of STAT5 phosphorylation in response to low-level (10 U/mL) IL-2. Significant reductions in STAT5 phosphorylation were also observed at higher levels (50 and 100 U/mL) of IL-2 (P = .005) (Figure 2C).

The effect of anti-CD25 antibody treatment on CD4+CD25+ Treg was analyzed by examining Foxp3 as a marker of Treg. Flow cytometric analysis (Figure 2D) demonstrated a reduction in mean fluorescence intensity of Foxp3 expression during treatment compared with baseline (P < .001) (Figure 2E). Reduction in Foxp3 expression at the single cell level during treatment is consistent with previous studies implicating STAT5 as a regulator of Foxp3 gene transcription. Furthermore, the frequency of total Foxp3-expressing CD4+ cells were reduced, with approximately 30% reduction in the mean frequency of CD4+Foxp3+ cells observed by month 2.5 and 44% reduction by month 7.5 (P < .001) (Figure 2F). Similar reductions were observed in the frequency of CD4+CD25+Foxp3+ cells (45% reduction; P < .001). Post-treatment samples available from a limited number of subjects demonstrated recovery of Treg frequencies to near baseline levels.
REDUCTION OF T_{reg} PROLIFERATIVE CAPACITY AND IMPAIRED T_{reg} SUPPRESSION BY ANTI-CD25 ANTIBODY TREATMENT

Based on the known role of IL-2 in promoting cell cycle progression in conventional T cells, we asked whether altered homeostatic proliferation of T_{reg} could account for the reduction in frequency of T_{reg} during treatment. The effect of anti-CD25 antibody treatment on T_{reg} proliferation was examined using Ki67 expression to estimate the in vivo proliferating fraction, determined as the proportion of CD4^{+}Foxp3^{+} cells expressing Ki67. The PBMC from baseline and treatment were stained ex vivo for intracellular expression of Ki67. Consistent with a pre-
vious study demonstrating high in vivo proliferative kinetics of human T<sub>reg</sub>, CD4<sup>+</sup> Foxp3<sup>+</sup> cells demonstrated high Ki67 expression at baseline compared with total CD4<sup>+</sup> cells (mean [SD], 11.7% [2.2%] vs 2.13% [0.8%], respectively). Analysis of treatment samples showed a reduction in the Ki67-expressing proliferating T<sub>reg</sub> fraction (<i>P</i> = .001) (Figure 3A), suggesting impaired homeostatic proliferation of T<sub>reg</sub> during anti-CD25 antibody treatment.

To assess T<sub>reg</sub> function, coculture suppression assays were performed to compare T<sub>reg</sub> suppression at baseline and during treatment. Because of altered CD25 expression during treatment, an additional surface marker, CD127, was used to sort T<sub>reg</sub>, which express low or no CD127 (CD127<sup>low/neg</sup>). The FACS analysis demonstrated that most CD4<sup>+</sup> Foxp3<sup>+</sup> cells were contained within the CD25<sup>+</sup> CD127<sup>low/neg</sup> subset at baseline and during treatment (Figure 3B). To determine the effect of anti-CD25 antibody treatment on T<sub>reg</sub> suppressive capacity, CD4<sup>+</sup> CD25<sup>+</sup> CD127<sup>low/neg</sup> cells were sorted by FACS from PBMC obtained at baseline and during treatment and cocultured with autologous CD4<sup>+</sup> CD25<sup>−</sup> CD127<sup>+ </sup>(responder) cells. Treatment samples demonstrated im-

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**Figure 3.** Regulatory T cell (T<sub>reg</sub>) in vivo proliferation and ex vivo suppression are impaired during anti-CD25 antibody treatment. A, Representative fluorescence-activated cell sorter (FACS) analysis comparing Ki67 expression in forkhead box P3 (Foxp3<sup>+</sup>) cells at baseline and during anti-CD25 antibody treatment (the percentage of Ki67-expressing cells is in parentheses). The bar graph compares the mean (SD) proportion of CD4<sup>+</sup> Foxp3<sup>+</sup> cells expressing Ki67 at baseline and during treatment (<i>P</i> = .001; n = 12). B, Representative CD4<sup>+</sup> gated FACS analysis showing that most CD4<sup>+</sup> Foxp3<sup>+</sup> cells (blue) are CD25<sup>+</sup> CD127<sup>low/neg</sup> during treatment. The numbers indicate the frequency of cells that are Foxp3<sup>+</sup> within the polygonal gate and, in parentheses, the percentage of total lymphocytes that are CD4<sup>+</sup> Foxp3<sup>+</sup> cells. C, Representative [<sup>3</sup>H] thymidine incorporation data (mean [standard deviation] counts per minute) shown for up to 5 × 10<sup>5</sup> FACS-sorted T<sub>reg</sub> (CD4<sup>+</sup> CD25<sup>+</sup> CD127<sup>low/neg</sup>) titrated in coculture with 5 × 10<sup>5</sup> responder (CD4<sup>+</sup>CD25<sup>−</sup>CD127<sup>+</sup>) cells. Closed circles represent cells from baseline and open circles represent cells obtained during anti-CD25 antibody treatment. D, Reduced suppressive capacity (mean [standard deviation] percentage of suppression) of circulating T<sub>reg</sub> during anti-CD25 antibody treatment (<i>P</i> = .03; n = 4).
paired $T_{reg}$ suppression compared with baseline samples ($P = .03$) (Figure 3C and D), indicating a functional impairment of ex vivo $T_{reg}$ suppression during anti-CD25 antibody treatment.

**LACK OF CORRELATION BETWEEN REDUCTION OF $T_{reg}$ AND ACUTE CENTRAL NERVOUS SYSTEM INFLAMMATION**

In addition to changes in $T_{reg}$ anti-CD25 antibody treatment led to significant alteration in conventional activated CD4$^+$CD25$^+$ T cells and CD56bright natural killer (NK) cells. The frequency of conventional activated T cells (CD4$^+$CD25$^+$Foxp3$^+$) was reduced during anti-CD25 antibody treatment ($P < .001$), which corresponded to the contraction of Ki67$^+$ proliferating fraction of conventional activated T cells. In contrast, the proportion of proliferating CD56$^+$ NK cells was increased during anti-CD25 antibody treatment and corresponded to the expansion of CD56$^{bright}$ NK cells observed during the course of therapy ($P < .001$).

In the setting of simultaneous changes to activated conventional T cell and NK cell compartments, $T_{reg}$ were not necessarily the major determinants of acute central nervous system inflammation. Contrast (gadolinium dithylenetriamine pentaacetic acid [Gd-DTPA]) enhancement of MS lesions on brain magnetic resonance imaging, a marker of MS inflammatory activity, was assessed on a monthly basis. The number of MS lesions demonstrating Gd-DTPA enhancement (Gd-DTPA$^+$ lesions) was significantly reduced during treatment with anti-CD25 antibody ($P < .001$) (Figure 4A). To assess whether the reduction in $T_{reg}$ had any negative effect on the immunomodulatory effect of anti-CD25 antibody, we analyzed the relationship between changes in the frequency of $T_{reg}$ and brain inflammatory activity. No significant correlations were observed between changes in the frequency of $T_{reg}$ and changes in brain inflammatory activity measured as the total number of Gd-DTPA$^+$ lesions per month ($r^2 = 0.0171; P = .69$) (Figure 4B) or the number of new Gd-DTPA$^+$ lesions per month ($r^2 = 0.0157; P = .71$) when assessed at month 7.5. Analysis of earlier and later time points (months 2.5 and 12.5) yielded similar results ($r^2 = 0.068$ and $r^2 = 0.0391$, respectively, for correlation between change in total number of Gd-DTPA$^+$ cells and $T_{reg}$).

**NEW-ONSET INFLAMMATORY DERMATITIS AS AN ADVERSE EVENT DURING ANTI-CD25 ANTIBODY TREATMENT**

Dermatitis occurred in 3 of 15 individuals who were taking anti-CD25 antibody (Table). The onset of dermatitis occurred during anti-CD25 antibody treatment in 2 subjects and at the end of treatment in one subject who nevertheless still demonstrated more than 80% saturation of CD25 at the onset of dermatitis. An additional subject with a family history of rheumatoid arthritis developed palindromic rheumatism during treatment. Reductions in the frequencies of Foxp3$^+$ cells for subjects who developed dermatitis are shown in the Table. Histologic examination of lesional skin from 2 subjects who developed dermatitis during treatment showed spongiotic to psoriasiform epidermal changes with perivascular lymphocytic inflammatory infiltrate in the subjacent superficial dermis (Figure 4C and D). In situ quantitative detection of Foxp3 in the lesional skin showed that approximately 13% of infiltrating CD3$^+$ cells were $T_{reg}$ (Figure 4E and F).

**COMMENT**

Here we demonstrate that long-term maintenance anti-CD25 antibody treatment led to sustained reduction of CD4$^+$CD25$^+$ $T_{reg}$ in subjects with MS. In contrast to the hypoproliferative nature of $T_{reg}$ in culture, we and others$^{22}$ find evidence that $T_{reg}$ exhibit high replicative capacity in vivo. Reduced proliferating $T_{reg}$ fraction corresponds to decline in $T_{reg}$ numbers in the setting of impaired IL-2 signaling and suggests that IL-2–supported $T_{reg}$ proliferation accounts for a substantial portion of the human circulating $T_{reg}$ pool. Clinical trials in patients with cancer demonstrated upregulation of Foxp3 and increased frequency of $T_{reg}$ following administration of IL-2. $^{23,24}$ Our data demonstrates, conversely, that negative perturbation of IL-2 signaling reduces Foxp3 expression and reduces the circulating $T_{reg}$ pool. Collectively, these studies indicate that IL-2 plays a major role in controlling the homeostatic set point for the size of the human circulating $T_{reg}$ pool.

We asked whether reduction in circulating $T_{reg}$ during anti-CD25 antibody treatment negatively affected MS inflammatory activity. Overall brain inflammatory activity was reduced during treatment, suggesting a shift toward tolerance. The lack of a correlation between changes in frequency of $T_{reg}$ and changes in brain inflammatory activity suggests that sustained reduction in circulating $T_{reg}$ did not negatively affect disease activity. One likely explanation is that simultaneous changes in other cell subsets during anti-CD25 antibody treatment countered any negative affect of reduced $T_{reg}$. Anti-CD25 antibody treatment led to a contraction of the CD4$^+$CD25$^+$ activated conventional T cell fraction and an expansion of CD56$^{bright}$ NK cells. A previous study demonstrated the capacity of CD56$^{bright}$ NK cells to suppress inflammation; expansion of CD56$^{bright}$ NK population is potentially a major determinant of acute brain inflammatory activity during anti-CD25 antibody treatment. $^{25}$ Alternatively, the lack of correlation between changes in circulating $T_{reg}$ and changes in brain inflammatory activity suggests the possibility that $T_{reg}$ are not a major determinant of acute inflammatory activity in MS. Data from experimental autoimmune encephalomyelitis, an animal model of MS, have not yet reconciled what role CD4$^+$CD25$^+$ $T_{reg}$ play in modulating acute central nervous system inflammation. Loss of $T_{reg}$ appears to confer susceptibility to experimental autoimmune encephalomyelitis in an otherwise resistant strain of mice, $^{26}$ but central nervous system antigen-specific $T_{reg}$ failed to inhibit central nervous system effector T cells during the acute phase of experimental autoimmune encephalomyelitis, possibly owing to the in situ cytokine milieu, particularly IL-6, that renders effector T cells resistant to $T_{reg}$ suppression. $^{27}$
Dermatitis occurred in 3 of the 15 subjects receiving treatment. An additional subject with a family history of rheumatoid arthritis developed migratory tenosynovitis during treatment, diagnosed as palindromic rheumatism. The incidence of new-onset inflammatory disease during anti-CD25 antibody treatment raised the possibility that there may be compartmental differences in the capacity to maintain tolerance in the setting of reduced circulating Treg. A recent study showed that CD4+CD25+ Treg contribute to routine immune surveillance and inflammatory response in the human skin.28 Furthermore, the availability of circulating Treg capable of mi-

Figure 4. Lack of correlation between reduction in the frequency of regulatory T cells (Treg) and changes in acute central nervous system inflammatory activity. A, Reduction in brain inflammatory activity indicated by reduction in the total number of contrast-enhancing multiple sclerosis (MS) lesions per month (total number of gadolinium dithylenetriamine pentaacetic acid [Gd-DTPA] lesions) on serial brain magnetic resonance images ($P < .001$; n=13). B, Regression analysis of correlation between change in total number of contrast enhancing lesions per month (percentage of reduction in Gd-DTPA+ lesions) and change in the frequency of circulating Treg (percentage of reduction in the number of Treg) at month 7.5 during anti-CD25 antibody treatment ($r^2=0.0171; P=.68$, Pearson correlation coefficient). C–F, Analysis of Treg in lesional skin. C, Hematoxylin-eosin (H&E)–stained tissue section (subject MS 9) showing epidermal changes of the skin lesion, characterized by compact hyperkeratosis, acanthosis, and focal spongiosis with exocytosis of lymphocytes (magnification $\times$20). D, H&E-stained section showing histologic changes in the superficial dermis, characterized by a perivascular chronic inflammatory infiltrate comprised predominantly of lymphocytes. E, Immunohistochemical staining for CD3. F, Immunohistochemical staining for forkhead box P3 (Foxp3).
Anti-CD25 antibody induction therapy on Treg is likely transient or modified by concomitant use of immunosuppressive agents. Evidence from skin biopsies taken from our subjects suggests that a functional defect of Treg may not be a universal feature across all patients with MS.

The collective clinical experience with anti-CD25 antibody treatment constitutes a large body of data that demonstrates its safety and efficacy as induction therapy in the prevention of allograft rejection and in the maintenance of skin-specific tolerance in an animal model. However, the relationship between reduction in Treg and new-onset inflammatory disease is inconclusive, and further work is required to determine whether there are compartmental differences in requirements for CD4+CD25+ Treg to maintain organ-specific tolerance.

A functional defect of CD4+CD25+ Treg cells has been reported in subjects with MS. We found no significant difference in mean Treg suppression between our cohort of subjects with MS and healthy donors, suggesting that either a functional defect of Treg may not be a uniform finding in all subjects with MS or that the differences are on a scale that requires a larger cohort to adequately power such comparisons. Studies comparing Treg suppression in subjects with MS and healthy volunteers suggest that the differences may be age-dependent or disease stage-dependent.

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