Prednisolone Treatment Induces Tolerogenic Dendritic Cells and a Regulatory Milieu in Myasthenia Gravis Patients

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Central thymic tolerance has evolved to prevent autoreactive cells from escaping into the periphery. However, self-specific T cells are frequently found in the peripheral blood even of healthy individuals (1). Thus, autoreactivity is an intrinsic feature of T cells and active suppression is required to maintain tolerance to self (2).

Among CD4+ T cells, different types of regulatory T cells (Treg) can be distinguished, such as naturally occurring and induced Treg (iTreg). Naturally occurring CD4+ CD25high Treg (nTreg) cells originate from the thymus as a functionally distinct population (3). They express constitutively high levels of CD25 (α-chain of the IL2 receptor) (4) and the forkhead box transcription factor 3 (FOXP3) (5). FOXP3 plays a crucial role during thymic nTreg development and in nTreg-mediated suppression (6), whereas IL-2 appears to be crucial for peripheral homeostasis and survival, at least in the mouse system (7).

iTregs are different from nTreg cells as they develop in the periphery from conventional CD4+ Th cells (8). Their development can be induced under tolerogenic conditions such as suboptimal antigen stimulation and the presence of immunoregulatory cytokines such as IL-10 and TGF-β. Moreover, immunosuppressive medication can lead to the development of tolerizing APCs, characterized by a low expression level of costimulatory molecules and an immunosuppressive cytokine milieu that in turn promotes the induction of Tregs (9, 10). Several types of induced Tregs have been described, such as the CD4+ type-1 Tregs (Tr1) (11), CD4+ CD25+ FOXP3+ cells (12), and Th3 cells (13). All of these iTreg types have been described to inhibit T cell-mediated responses. Tr1 cells are also able to produce high levels of IL-10 and moderate levels of TGF-β that again promote an immunosuppressive environment (8).

Tregs can prevent autoimmune pathology in different experimental models (14). In humans, defects in Treg cell function have been described in several autoimmune diseases, such as multiple sclerosis (15) and autoimmune diabetes (16, 17) while Treg cells are enriched and functionally active in inflamed joints of patients with rheumatoid arthritis (18).

Myasthenia gravis (MG) is a CD4+ T cell-dependent autoimmune disease mediated by pathogenic autoantibodies specific for the acetylcholine receptor (AchR) (19). The disease is controlled by AchR-specific T cells found in the thymus and peripheral blood of MG patients. The presence of the pathogenic T cells within the myasthenic thymus suggests that the disease is initiated in the pathologically transformed thymus (20, 21). Corticosteroids, especially prednisolone (pred), are the treatment of choice for many MG patients (22), because they seem to be effective in inducing...
remission in a large cohort of patients. The effects of corticoste-
roid, and pred in particular, are manifold, including inhibition of
IL-2 production and dendritic cell (DC) function (23, 24).

We have previously shown that the peripheral frequency of Treg
cells in MG patients is unaltered when compared with age-
matched healthy donors (25). Moreover, Balandina and colleagues
(26) showed reduced suppression by thymic Treg from MG pa-
tients. Peripheral Treg were not assessed in this study. In this
study, we show that the suppressive capability of peripheral blood
Treg in untreated MG patients is profoundly impaired. Even more
striking, MG patients treated with pred showed a considerable
improvement in their Treg cell function. Our data support the hy-
thesis that pred-induced tolerogenic DCs are involved in the
generation of peripheral Tregs that in turn ameliorate the clinical
picture of MG.

Materials and Methods

Patients
Peripheral blood was obtained upon informed consent from 19 patients
diagnosed with MG according to standard clinical criteria and all positive
for AChR Abs (age range 35 to 85), and 27 age-matched healthy donors
(age range 27 to 71). MG patients were divided into two groups according
to their treatment: 1) MG patients treated (t-MG) with azathioprine (Aza)
and pred or pred alone (supplemental Table Ia)7) and 2) MG patients that
were not treated (ut-MG) with any immunomodulatory drug for at least
1 year before blood collection (supplemental data, Table Ib).

Isolation of Tregs

CD4+CD25− and CD4+CD25high cells were isolated from freshly pre-
pared PBMCs using Ab-tagged magnetic microbeads (CD4+CD25− Reg-
ulatory T Cell Isolation Kit, Miltenyi Biotec). CD4+ T cells were first
isolated by negative selection, and subsequently separated into CD4+CD25−
and CD4+CD25+ fractions using anti-CD25 magnetic beads. The
positively selected CD25high T cells were run over a second column to
ensure higher purity. Alternatively, cells were sorted on the basis of CD4+CD25
and CD25high after staining with CD4-Pacific Blue (DakoCytomation) and
CD25-PE (Miltenyi Biotec) in the FACS Aria (BD Biosciences). In all cases,
the purity of the Treg population was between 90 and 98% as assessed by flow
cytometry.

Proliferation and suppression assays

CD4+CD25− responder T cells (Tresp, 1 × 106 well) were cultured with
different ratios of CD4+CD25high Treg cells (Tresp:Treg=1:1, 1:0.5, 1:0.25,
and 1:0.125) in the presence of 1 μg/ml anti-CD3 (clone OKT3) and
1 × 103 irradiated allogeneic PBMCs (33 Gy) in T cell medium (RPMI
1640 with t-Glutamine and 25 mM HEPES, Invitrogen) supplemented with
10% human AB serum (PAA Laboratories) and antibiotics (PAA Labora-
tories). Cells were cultured in triplicates or quadruplicates in BD Falcon
flat-bottom 96-well plates (BD Biosciences) in a total volume of 200 μl
T cell medium. After 3 days in culture, 1 μl of [3H]thymidine (Amersham
Biosciences) was added to the culture for an additional 16 to 18 h. Cells
were then harvested and thymidine incorporation was measured using a
scintillation counter (Applied Biosystems). Suppression of IgG production
by Treg cells was measured as previously described (27). In brief, B and
Treg cells were isolated using magnetic beads (Miltenyi Biotec) and stim-
ulated overnight with 5 μg/ml pokeweed mitogen (PWM, B cells) or 1
μl/ml superantigen (SEB, Treg cells) (Sigma-Aldrich) and subsequently
cocultured at 1:1 ratio in the presence of cytokines (IL-2, IL-4, and IL-10,
all from Tebu-bio) and CD40L-transfected NIH 3T3 cells to promote Ab
secretion by B cells. After 5 days, culture supernatants were assessed for
IgG by ELISA (Immunology Consultants Laboratory). Anti-CD25-FITC was
added when necessary. Stimul-
taneously, cells from the same donor were also stained with CD4+ PB, CD8-
allophycocyanin, and CD25-PE (Miltenyi Biotec) on the cell surface to
assess the percentage of CD4+CD25bright Treg cells. FACS analysis was
performed using the Cyan and the Summit software (DakoCytomation).
The percentage of Treg cells on the basis of CD25 expression was calcu-
lated with the CD4+ and CD25+ population or, if not possible, a thresh-
old was set at 0.1% on the non-CD4 cells (used as a control) in the CD4/
CD25 dot plot (25). FOXP3 expression in CD4+ and CD25+ T cells were
assessed after intracellular staining for CD4, CD8, and FOXP3. FOXP3 expression
was calculated after gating on CD4+ and CD8+ T cells by setting the
threshold with the negative population, which is clearly distinguishable from
the FOXP3+ cells.

Generation of DCs

Monocytes were isolated from PBMCs using the human CD14+ micro-
beads from Miltenyi Biotec. Monocytes were cultured in RPMI 1640 containing
10% FCS supplemented with 100 ng/ml GM-CSF (Leukomax)
and rhl-4 (40 ng/ml ImmunoTools) for 5 days. DC maturation was
induced by the addition of the 5 μg/ml LPS (Streptococcus typhii, Sigma-
Aldrich) for 24 h. Pred (1 μM, Solu-Decortin H, Merck) was added for 48 h
before LPS stimulation. DCs were collected, irradiated at 60 Gy and
either used directly or cryopreserved until needed for in vitro stimulation.
Phenotype and maturation state of differentially treated DCs was assessed by
measuring the expression level of CD1c, CD80, CD86, CD83, and
HLA-DR (all Abs were purchased from BD Biosciences) by FACS.

Real-time PCR

Total RNA was extracted with the RNeasy Micro Kit from Qiagen
and subsequently reverse transcribed for mRNA analysis. The template cDNA
was amplified using specific primers, the MGB probe system and the Taq-
Man Universal Master Mix in the ABI Prism 7000 Detection System (Ap-
plied Biosystems). PCR conditions were as follows: 50°C for 2 min, 95°C
for 10 min, 40× 95°C for 15 s, and 60°C for 1 min. Samples were run in
duplicates. The FoxP3 specific primer and MGB-probe system was
purchased from Applied Biosystems (Assay-on-Demand, Applied Biosys-
tems). Additional oligonucleotides used in that study are as follows: IL-1β
forward 5′-TGA TGG CTT ATT ACA GTG GCA ATG; IL-1β reverse
5′-GTA GTG GTG GTG GGA GAT GAT TGC-3′; IL-6 forward 5′-TCT
CCA CAA GAG GCT TCG-3′; IL-6 reverse 5′-CTC AGG GCT GAG ATG
CCG-3′; IL-10 forward 5′-GTG TTA CCT GGA GGA GGT GAT-3′;
IL-10 reverse 5′-GGC CCT GCT GCT GTT TTC AC-3′; TGF-β forward
5′-GCC CTG GAC ACC AAC TAT TG-3′; TGF-β reverse 5′-CTG GTC
CAG CAG CCA AAT-3′. As an endogenous control and for normalization
of the starting amount of total RNA, the 18S rRNA gene was amplified
using: 5′-CGG CTA CCA CAT CCA AGG AA-3′ and 5′-GCT GGA ATT
AAG GGG GCC GGT-3′ and the SybrGreen PCR Master Mix (Applied
Biosystems).

ELISA

Supernatants were collected from DCimm, DCmat, and DCpred,LPS after
7 days of culture to assess the amount of IL-12 and IL-23. Cytokine produc-
tion was determined using the respective capture ELISA following the
manufacturer’s instructions (IL-12: R&D Systems; IL-23: eBiosciences).
The detection limits were 62.5 pg/ml for IL-12 and 15 pg/ml for IL-23.
The analysis was performed in triplicates and the cytokine levels were calcu-
lated from the standard curve.

T cell differentiation assay

In brief, 0.4 × 105 DCimm, DCmat, or DCpred,LPS were cultured with mag-
netic bead-purified CD4+CD25− T cells at a ratio of 10:1 in T cell medium
in a 24-well plate. After 7 days, 40 U/ml human rIL-2 (Chiron) was added,
and cells were expanded for another 7 days. Fourteen days after initiation
of the culture, T cells were collected, washed, and restimulated with
DCimm, DCmat, and DCpred,LPS from the same allogeneic donor used in the
primary culture. After 3 days, 40 U/ml HIL-2 were added. One week after
the second stimulation, CD4+ T cells were collected and their phenotype
as well as their proliferative and suppressive capacity were analyzed. In
some experiments, CD4+ T cells were restimulated for a third time. In
some experiments, 20 μg/ml blocking IL-10R Ab (BD Biosciences) were
added every 2–3 days for the entire culture period.

Suppression assay

To test the suppressive activity of the CD4+CD25high Cells generated in
the T cell differentiation assay, freshly isolated CD4+CD25− T cells were
labeled with 10 μM CFSE (carboxy-fluorescin diacetate-succinimidyl
ester) (Molecular Probes, Eugene, OR) for 15 min at room temperature. The

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7) The online version of this article contains supplemental material.
Impaired suppressive function of nTreg derived from MG patients. A, CD4⁺CD25<sup>high</sup> Treg cells from 27 healthy controls and 19 MG patients were analyzed for their suppressive potential. Tresp and Treg cells were cultured for 4 days at different ratios in the presence of allogeneic stimulation and 1 μg/ml soluble anti-CD3. Proliferation was measured by [³H]thymidine incorporation. A, The diagram represents the average suppressive potential at a 1:1 ratio of Tresp:Treg ± SEM in healthy donors (■) and MG patients (□). B and C, Five representative individual proliferation assays from HD and MG patients, respectively.

Statistical analysis

The mean [³H]thymidine uptake was calculated from triplicates or quadruplicates. Unpaired two-tailed Student’s t test was used to compare the suppression and percentages of CD25<sup>high</sup> and FOXP3-expressing cells between MG patients and healthy donors, or between treated and untreated patients. The chosen global significance level was $p < 0.05$. Error bars represent the SEM.

Results

nTreg-mediated suppression is impaired in patients with MG

Previous studies have shown that Treg cells are present with the same frequency in the periphery of both MG patients and healthy donors (HD) (25). To analyze the functional capabilities of these cells, we cultured highly pure CD4⁺CD25<sup>high</sup> Treg cells from MG patients and healthy donors together with autologous responder CD4⁺CD25⁻ T cells (Tresp) (Fig. 1A). CD4⁺CD25⁻ Tregs from healthy donors consistently suppressed the proliferation of Tresp cells (average suppression 34.44%; Fig. 2A). This is in contrast to Tregs from MG patients, as it has been shown for other autoimmune diseases.

Steroid treatment partially restores nTreg-mediated suppression

Pred is the treatment of choice for patients that do not respond to oral anti-cholinesterase treatment. To investigate whether treatment with pred has any effect on Treg-mediated suppression, we compared the suppressive potential of CD4⁺CD25<sup>high</sup> cells isolated from ut-MG and from pred-treated MG patients. Although the CD4⁺CD25<sup>high</sup> population purified from ut-MG patients showed only marginal suppression at a 1:1 ratio of Tresp and Treg cells (average suppression 34.44%; Fig. 2A), a much stronger suppression was observed when using CD4⁺CD25<sup>high</sup> cells from t-MG patients (Tresp:Treg 1:1; 51.06%, Fig. 2A), although it did not reach the levels of suppression achieved by the healthy donor.
cohort. However, suppression mediated by CD4<sup>+</sup>CD25<sub>high</sub> cells from t-MG patients was enhanced at all tested ratios of Tresp and Treg cells when compared with ut-MG patients.

Although MG is a CD4<sup>+</sup> T cell-dependent disease, the pathophysiology is mediated by autoantibodies directed against the AChR. To assess whether the failure of Treg in MG patients to suppress T cell responses also extends to the B cell compartment, and whether this defect in suppression can be reversed by in vivo pred treatment, we measured direct Treg-mediated suppression of Ab production (from HD and MG patients). We found that Treg cells from ut-MG are compromised in suppressing IgG production by B cells (average suppression of IgG production was 2.8%; Fig. 2B) in comparison to HD (20.9%, p < 0.05). In contrast, two of the three patients in the treated group showed suppression values close to healthy donors. Our data show that CD4<sup>+</sup>CD25<sub>high</sub>-mediated suppression of both T and B cell responses is especially compromised in ut-MG patients and it is partially restored in MG patients treated with pred.

The levels of FOXP3 expression are similar in healthy donors and MG patients

FOXP3 is considered a master regulator for the control of Treg development and function (6). We hypothesized that the defect in the suppressive capacity of CD4<sup>+</sup>CD25<sub>high</sub> cells from MG patients could be related to lower than normal levels of FOXP3 that would result in an impaired Treg function in patients. To check this, peripheral blood from 14 MG patients (range from 35–80 years of age) and 17 healthy controls (range from 21–48 years of age) was analyzed for the expression of CD25 and of FOXP3 in CD4<sup>+</sup> T cells at the protein level by flow cytometry. A triple surface staining for CD4, CD8, and FOXP3 was used for the detection of FOXP3-expressing CD4<sup>+</sup> cells (Fig. 3A, left), while intracellular staining for CD4, CD8, and FOXP3 was used for the detection of FOXP3-expressing cells (Fig. 3A, right). The frequency of CD4<sup>+</sup>CD25<sub>high</sub> cells in healthy donors averaged 3.48% (range 0.70–6.98%) and in MG patients 2.45% (range 0.61–6.85%; Fig. 3B), differences that did not reach statistical significance (p = 0.1895). Similarly, the average frequency of circulating FOXP3<sup>+</sup> in CD4<sup>+</sup> T cells from healthy controls was 6.82% (range 3.26–9.88%) and in MG patients 6.71% (range 2.03–16.84%), which was again not statistically significant (p = 0.38; Fig. 4C). Of note, the frequency of FOXP3<sup>+</sup> cells was in all cases higher than the frequency of CD25<sub>high</sub> cells.

To analyze the expression level of FOXP3 on a per cell basis, we calculated the ratio of the median fluorescence intensity (MFI) between CD4<sup>+</sup>FOXP3<sup>+</sup> and CD4<sup>+</sup>FOXP3<sup>−</sup> cells. The average MFI for healthy controls was 5.35 (range 2.05–11.54) and from MG patients 6.65 (range 2.13–10.34; Fig. 3D) representing a non-statistically significant difference. To correlate the levels of FOXP3 expression with suppressive activity, we categorized the expression levels of FOXP3 in CD4<sup>+</sup> T cells in three different groups according to the MFI (low: MFI < 4, medium: MFI 4 and ≤ 7 and high: MFI > 7) and calculated whether the quality of CD4<sup>+</sup>CD25<sub>high</sub>-mediated suppression is reflected by the expression level of FOXP3. We found that the high variation among FOXP3 expression did not mirror Treg-mediated suppression (Fig. 3E). For instance, CD4<sup>+</sup>CD25<sub>high</sub> cells isolated from a donor with medium FOXP3 expression (D6; MFI 5.82) showed the highest suppression (suppression of 97.12%) while CD4<sup>+</sup>CD25<sub>high</sub> cells from donors with a high FOXP3 MFI (D2; MFI of FOXP3 11.54, suppression of 63.24%) and low FOXP3 MFI (D1; MFI of FOXP3 3.92, suppression of 64.09%) showed almost the same suppressive capability. We also compared average FOXP3 MFI from t-MG patients (average 7.61 ± 1.16) with that from ut-MG patients (av-

**FIGURE 3.** Comparable expression levels of CD25 and FOXP3 in MG patients and HD. The peripheral frequency of CD4<sup>+</sup>CD25<sub>high</sub> and CD4<sup>+</sup>FOXP3<sup>+</sup> T cells was analyzed in 19 HD and 14 MG patients by flow cytometry. A, Example of FACS staining of peripheral blood lymphocytes for surface CD25 (left) and intracellular FOXP3 (right) expression in gated CD4<sup>+</sup> T cells. The frequency of CD25<sub>high</sub> cells was assessed on the basis of CD4<sup>low</sup> and CD25<sub>high</sub>. The frequency of FOXP3<sup>+</sup> cells expression was assessed on gated CD4<sup>+</sup> by setting a threshold with the negative population. B and C, Frequencies of CD4<sup>+</sup> CD25<sub>high</sub> (B) and CD4<sup>+</sup> FOXP3<sup>+</sup> (C) in MG patients and HD. D, The MFI of FOXP3<sup>+</sup> in CD4<sup>+</sup> T cells is shown for HD and MG patients. The average ± SEM is shown for each graph. NS; non-significant. E, Lack of correlation between FOXP3 expression and nTreg-mediated suppression. The levels of FOXP3 expression (left axis) and suppressive potential (right axis) of peripheral blood nTreg cells from six healthy donors (D1 to D6 from left to right) was analyzed as described above.
treated with either 1 μM pred (DCpred) or 5 μg/ml LPS (mature DCs, DCmat). Phenotypical analysis revealed that immature DCs expressed low levels of CD80, CD83, and CD86 (Fig. 4A). Treatment of DCs with pred alone did not alter the expression level of these costimulatory molecules when compared with DCimm. As expected, LPS-stimulated DCs up-regulated surface expression of CD80, CD83, and CD86. Interestingly, pred-pretreated DCs showed only a moderate up-regulation of CD86 after induction of maturation with LPS while the expression level of CD80 was comparable to that of DCmat (Fig. 4A). We could not detect any differences in the MFI of HLA-DR between DCimm, DCmat, DCpred, and DCpred,LPS (data not shown). Next, we studied the cytokine profile of differentially treated DCs and found that transcripts for the proinflammatory cytokines IL-6 and IL-1β were most abundant in DCmat and practically absent in DCimm. Preincubation of DCs with pred before LPS stimulation totally abrogated IL-6 expression in DCs, and it reduced the transcription of IL-1β by 50% (Fig. 4B). Similarly, when supernatants from the DC cultures were assessed for IL-12 and IL-23, cytokines that promote differentiation of CD4+ Th cells into T_{H1} (IFN-γ-producing cells) and T_{H17} (IL-17-producing cells), respectively, we found that LPS-matured DCs showed highest secretion levels of IL-12 (2051 pg/ml) and IL-23 (1661.4 pg/ml) while preincubation with pred resulted in a marked decrease in IL-12 (300.25 pg/ml) and IL-23 (662.4 pg/ml) (Fig. 4C). In contrast, RNA transcripts for the immunomodulatory cytokines IL-10 and TGF-β were higher in the cells that had been preincubated with pred, independently of the maturation stimulus provided by LPS.

Taken together, these data demonstrate that DCs pretreated with pred maintain an immature state even in the presence of the LPS, and produce preferentially the immunomodulatory cytokines IL-10 and TGF-β rather than their proinflammatory counterparts IL-6, IL-12, or IL-23, suggesting that DCpred,LPS may induce CD4+ T cell tolerance rather than a potent immune reaction.

Modulation of DC function in patients treated with pred

In vitro treatment of mo-DCs with pred before LPS challenge prevents these cells from full maturation. We wondered whether the same effect is observed in cells derived from MG patients, and, more importantly, if DCs generated from patients treated with pred show any signs of impaired maturation to LPS stimulus. To test this, mo-DCs generated from ut-MG and t-MG blood samples were treated with pred in the presence or absence of LPS as described above and compared with mo-DC from HD treated in the same way. Phenotypic analysis revealed that the expression of CD86 was markedly reduced in all HD, six untreated MG patients, and four pred-treated patients is shown.

FIGURE 4. Pred pretreatment prevents full maturation of DCs and inhibits the production of inflammatory cytokines. A, Mo-derived DCs were either left unstimulated (DCimm) or treated with 1 μM pred (DCpred) or with 5 μg/ml LPS in the absence (DCmat) or presence of 1 μM pred (DCpred,LPS) and analyzed by flow cytometry for the expression level of CD80 (n = 6) and CD86 (n = 4). B, The cytokine profile of differentially treated DCs was analyzed by quantitative real-time PCR. RNA was isolated from DCimm, DCmat, DCpred, and DCpred,LPS and tested for the expression of IL-6, IL-1β, IL-10, and TGF-β. Data are representative of four individual experiments. C, Culture supernatants from the treated mo-derived DC were analyzed for the presence of IL-12 and IL-23 by ELISA and one representative experiment is shown.

FIGURE 5. Modulation of DC function in patients treated with pred. Mo-derived DCs from six HD, six untreated MG, and four pred-treated MG patients were treated as in Fig. 4 and analyzed by flow cytometry for the expression of CD86 and CD80 (A). The asterisk denotes statistical significance for the decrease in the percentage of CD86 ut-MG vs t-MG samples. * p = 0.032 Culture supernatants from the treated mo-derived DC were analyzed for secreted IL-12 by ELISA (B). The average of six HD, six untreated MG patients, and four pred-treated patients is shown.
after LPS stimulation was comparable to that of HD. In contrast, DCs generated from t-MG patients up-regulated CD80 only marginally upon LPS stimulation. Similarly, the production of IL-12 by mo-DCs from ut-MG was comparable to that of HD upon LPS challenge. However, in vivo pred treatment of patients severely compromised the ability of mo-DCs to produce IL-12 upon stimulation with LPS (Fig. 5B). As expected, in vitro addition of pred to these cells had no further effect in IL-12 production. Altogether, these data show that pred, both in vitro and in vivo, modulates the maturation of DCs, preventing the up-regulation of costimulatory molecules, and reducing the production of proinflammatory cytokines.

**Pred-treated DCs render CD4⁺ T cells hyporesponsive**

CD4⁺ T cells primed with allogeneic immature DCs are hyporesponsive to stimulation whereas CD4⁺ T cells cultured in the presence of LPS-stimulated DCs do proliferate (28). We hypothesized that DCpred,LPS, given the reduced costimulatory potential and the immunomodulatory cytokines produced, would behave tolerogenic. Thus, we assessed the capacity of DCpred,LPS to stimulate the proliferation of allogeneic CD4⁺ T cells. CD25-depleted CD4⁺ T cells were cultured in the presence of DCimm, DCmat, or DCpred,LPS at a 10:1 ratio. One week after the second stimulation, the CD4⁺ T cell lines were harvested and tested for their proliferative capacity in response to 1 μg/ml anti-CD3 and allogeneic irradiated PBMCs. In agreement with published data, CD4⁺ T cell lines stimulated by mature DCs proliferate upon polyclonal stimulation while CD4⁺ T cells stimulated with DCimm are hyporesponsive. In contrast, CD4⁺ T cells primed with DCpred,LPS were hyporesponsive to polyclonal stimulation (Fig. 6).

**CD4⁺ T cells differentiated in the presence of pred-treated DC are suppressive**

Low proliferation to stimulation is a characteristic of Tregs. We therefore tested the suppressive capacity of CD4⁺ T cells generated after repetitive stimulation with DCpred,LPS (CD4⁺-DCpred,LPS). To this end, freshly isolated CD4⁺CD25⁻ T cells were cultured with irradiated allogeneic APCs and soluble anti-CD3 for 4 days in the presence or absence of purified CD4⁺-DCpred,LPS, generated as above, and proliferation was measured by CFSE dilution. As expected, CD4⁺-DCmat had no suppressive effect on CD4 Tresp proliferation, and CD4⁺-DCimm showed minimal suppression capability (<10%). In contrast, DCpred,LPS elicited a relevant 24.7% suppression of proliferation of autologous CD4⁺CD25⁻ responder cells (Fig. 7), which was abrogated when the regulatory CD4⁺ cells were generated in the presence of blocking the IL-10R Ab during stimulation with DCpred,LPS (data not shown). These data show that CD4⁺ T cells generated by repeated stimulation with pred-treated LPS-stimulated DCs acquire the potential to suppress Tresp proliferation, and that the induction of the regulatory phenotype is dependent on IL-10.

**Discussion**

Immune tolerance to self and innocuous Ags is a basic mechanism to prevent self-destruction. Tregs play a critical role in the maintenance of peripheral tolerance and a distorted function of these cells can contribute to the development and course of autoimmune diseases. Several published studies have reported abnormalities in the Treg population, either in the frequency or in their in vitro function, or both, that could be related to different types of autoimmune diseases (15, 18). In MG, a T cell-dependent autoimmune disease, nTreg cells were shown to be present with the same frequency in the periphery when compared with healthy donors but their functional attributes were not yet assessed (25). Baldanina et al. (26) highlighted a defect in the regulatory activity of CD4⁺CD25⁺ thymocytes and a decrease in the FOXP3 expression within this population when isolated directly from the thymus of MG patients. FOXP3 is the only known lineage-specific marker for nTreg cells (5, 29). The importance of FOXP3 in Treg cell function is underlined in patients suffering from an immune dysfunction polyendocrinopathy enteropathy X-linked syndrome caused by mutations in the foxp3 gene (30, 31). Although we could demonstrate that the defective regulatory capacity is also present in peripheral Treg in MG patients, our data show that this is not due to a decreased expression of FOXP3: 1) there is no significant difference in the percentage of FOXP3⁺ cells between patients and healthy donors, 2) the levels of expression (MFI) are also not different, and 3) the level of FOXP3 expression did not correlate with suppressive function, as described also by others (32). There is conflicting data about the role of FOXP3 in suppression, with recent work showing that transient FOXP3 expression in recently activated CD4⁺CD25⁻ T cells could (33) or could not (34) exert suppressive functions. FOXP3 in humans exists in two isoforms, the full length and a splice variant lacking exon 2 (FOXP3Δ2). Retroviral transfer of either or both FOXP3 isoforms into naive CD4⁺ T cells led to the development of a regulatory phenotype. However, these converted Treg cells did not reach the suppressive potential of ex vivo isolated CD4⁺CD25high T cells (35). Thus, it is conceivable that FOXP3 does not represent the only regulator of Treg function, but rather contributes to regulate a network of molecules that control the development and function of nTreg cells.

MG is known to be a heterogeneous disease and the patient cohort we analyzed was fairly different according to MG classification. However, no significant difference in Treg-mediated suppression was observed when MG samples were subdivided according to disease onset.

![FIGURE 6.](http://www.jimmunol.org/)

**FIGURE 6.** CD4⁺ T cells derived after coculture with DCpred,LPS are hyporesponsive to polyclonal stimulation. CD4⁺CD25⁻ Tresp cells were cultured for three rounds of stimulation with irradiated CD4⁺CD25⁻ or DCpred,LPS. Seven days after the last restimulation, cells were harvested and tested for their ability to respond to 1 μg/ml anti-CD3 and irradiated allogeneic PBMCs. Proliferation was measured after 4 days by thymidine incorporation. One representative experiment of three is shown.

![FIGURE 7.](http://www.jimmunol.org/)

**FIGURE 7.** CD4⁺ T cells derived from DCpred,LPS-stimulated cultures suppress CD4⁺ T cell proliferation. CD4⁺ T cell lines generated with the differentially stimulated DCs were tested for their ability to suppress autologous CD4⁺CD25⁻ T cell proliferation to allogeneic DCs and soluble anti-CD3. Ex vivo isolated CD4⁺CD25high cells from the same donor were used as a positive control for suppression. Proliferation was measured after four days by CFSE dilution. One representative experiment of three is shown.
or the presence of a MG-associated thymoma. We found, however, that Tregs isolated from MG patients treated with pred showed an improved regulatory function compared with the Tregs from untreated patients. This effect was not only observed with respect to T cell proliferation but also to the B cell response, i.e., IgG production.

Corticosteroids are well known for their anti-inflammatory and immunomodulatory properties (36–38). Pred is the treatment of choice for patients that do not respond to acetylcholinesterase inhibitors, and it is often given together with Azα, to avoid some of the secondary effects that accompany steroid treatment. Azα is an inhibitor of DNA and RNA synthesis, thus affecting the proliferation of immune cells (39), but with no immunomodulatory effect. Because of the lack of immunomodulatory properties of Azα, and that the presence or absence of this complementary drug did not change the improved suppression in the treated patients, we did not separate patients treated with one or with the two drugs any further. The improved suppression potential of Tregs from pred-treated patients led us to hypothesize that 1) pred has a direct positive impact on Treg cells by the up-regulation of FOXP3 or other yet unknown molecules that direct their function and/or 2) Treg cells are generated de novo by pred-induced tolerogenic APCs. Because we could not demonstrate any direct effects of pred on Treg function, we sought to assess whether other cells could contribute to the improvement of regulatory function observed in pred-treated patients.

DCs represent the most potent APCs and are essential in immune system regulation (40). DCs can have dual functions; while mature DCs are potent T cell stimulators (reviewed in Ref. 41), immature DCs can induce T cell tolerance (28, 42, 43). Anti-inflammatory glucocorticoids are promising agents for developing tolerogenic DCs and thus the effect of pred on mo-DCs was evaluated (44, 45). In agreement with previous data (24), we found that pred-treated DCs maintain an immature state in the presence of maturation stimuli such as LPS. The up-regulation of costimulatory molecules was diminished suggesting that DCpred,LPS may induce T cell tolerance rather than a potent immune response. This supposition was also based on increased RNA levels of IL-10 and TGF-β in DCpred,LPS, known immunomodulatory cytokines, and reduced secretion of the proinflammatory cytokines IL-12 and IL-23 (46). Although IL-12 is known for activating DCs and promoting the differentiation of CD4+ T cells into Th1 cells, IL-23 is involved in the generation of Th17 cells and the induction of chronic (autoimmune) inflammation (47). We further studied the consequence of in vitro pred treatment on mo-DCs generated from patients that were untreated or pred treated. Mo-DCs generated from untreated MG responded to the treatment applied in vitro in the same way as mo-DCs from HD did. Interestingly, we observed in this study for the first time an impaired up-regulation of CD80 and IL-12 production by mo-derived DCs from pred-treated MG patients, suggesting that in vivo pred treatment can effectively modulate DC maturation.

The tolerogenic properties of DCpred,LPS were documented with the hyporesponsiveness of CD4+ T cell lines raised using treated DCs as APCs. The extend of induced anergy was similar to that of CD4+ T cells that have been precultured with DCimm in agreement with published results (48, 49). Induced Tregs develop from conventional CD4+ T cells in the periphery under tolerizing conditions such as a suboptimal antigenic stimulation (50), in the presence of immunomodulatory cytokines like IL-10 and TGF-β (51) or after administration of immuno-suppressive drugs (10, 52). Based on that observation, it was of great interest to test the potential of DCpred,LPS to generate Tregs, especially after having disclosed their potential to induce anergy. After repetitive exposure of CD25-depleted CD4+ T cells to allogeneic DCpred,LPS, we found that CD4+-DCpred,LPS were able to down-modulate CD4+ T cell proliferation in the presence of polyclonal stimulation to a greater extend than their counterparts that were cultured with DCimm. Blocking IL-10R during the generation of the Tregs resulted in the partial abrogation of their suppressive capacity, confirming IL-10 as a necessary factor for the induction of a regulatory phenotype (53). In these experiments, great emphasis was given to the depletion of CD25-expressing cells from the starting CD4+ T cell population and the purity of the remainder CD4+CD25- cell population was monitored before coculturing with DCs. Although unlikely, we cannot completely exclude the possibility that limited numbers of residual CD4+CD25high cells after depletion from the CD4+ pool survive and expand in cultures with DCimm and DCpred,LPS and contribute to the down-modulation of Tresp proliferation. Given the fact that CD4+ T cells cultured with DCnat do not suppress proliferation of freshly isolated Tresp cells while CD4+ T cells cultured with DCpred,LPS do, we favor a scenario in which Tregs are newly generated from the starting CD4+CD25- T cell population. Supporting our finding, the in vivo administration of a pred derivate prevented the development of colitis in mice due to potent IL-10 production and probably Treg induction (54).

Adaptive Tregs can be of different nature (11, 50, 55). Phenotypically, they are diverse in terms of FOXP3 expression, and in the cytokines that they produce, probably depending on the conditions that induce their differentiation. In addition, it is now known that FOXP3 can be expressed transiently in non-Treg cells upon activation, suggesting that this molecule may harbor a more diverse set of functions as assumed originally (56, 57). In our experiments, the expression of FOXP3 was comparable in all three CD4+ T cell lines after stimulation with differentially generated DCs (data not shown). This fact could just simply reflect recently activated and dividing cells present at each time point while the actual Tregs generated in the presence of DCpred,LPS do evolve and exert their suppressor function independent of FOXP3 (33). This assumption is supported by the finding that in vitro generated Tr1 cells do not constitutively express FOXP3 but they still suppress T cell proliferation efficiently (53, 58).

We demonstrate in this study for the first time an impaired suppressive potential of peripheral Treg cells from MG patients. In addition, we show that patients treated with pred displayed better suppression than untreated patients, although not to the levels of healthy donors. We had the chance to measure suppression before and after steroid treatment in two MG patients, and in both cases, the suppressive ability of Treg cells improved after pred treatment (data not shown). In addition, we have shown a modulatory effect of pred on mo-derived DC and the induction of regulatory cells after exposure to pred-treated DCs, and that this mechanism is IL-10 dependent, as it has been shown using different models (43, 59). Multiple factors might contribute to the improved suppression of T cell proliferation in treated patients, but we favor de novo generation of induced Tregs.

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Disclosures
The authors have no financial conflict of interest.

References


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Supplemental data

Table 1a. Patient data of treated MG patients.

Patients’ samples were classified according to standard clinical criteria: Early Onset MG (EO-MG), patients with disease onset before 40 years of age; Late Onset MG (LO-MG), patients with disease onset after 40 years and patients with MG-associated thymoma (MG-T).

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Table 1b. Patient data of untreated MG patients.

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Prednisolone-mediated immune regulation in MG patients.

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