Published February 7, 2011



# Defective IL-10 signaling in hyper-IgE syndrome results in impaired generation of tolerogenic dendritic cells and induced regulatory T cells

Masako Saito,[1] Masayuki Nagasawa,[2] Hidetoshi Takada,[4] Toshiro Hara,[4] Shigeru Tsuchiya,[5] Kazunaga Agematsu,[6] Masafumi Yamada,[7] Nobuaki Kawamura,[7] Tadashi Ariga,[7] Ikuya Tsuge,[8] Shigeaki Nonoyama,[9] Hajime Karasuyama,[1,3] and Yoshiyuki Minegishi[1,3]

[1]Department of Immune Regulation, [2]Department of Pediatrics and Developmental Biology, and [3]Core Research for Evolutional Science and Technology, Japan Science and Technology Agency, Tokyo Medical and Dental University Graduate School, Bunkyo-ku, Tokyo 113-8519, Japan
[4]Department of Pediatrics, Kyushu University, Higashi-ku, Fukuoka 812-8581, Japan
[5]Department of Pediatrics, Tohoku University, Aoba-ku, Sendai 980-8575, Japan
[6]Department of Pediatrics, Shinshu University, Matsumoto 390-8621, Japan
[7]Department of Pediatrics, Hokkaido University Graduate School of Medicine, Kita-ku, Sapporo 060-8638, Japan
[8]Department of Pediatrics, Fujita Health University, Toyoake 470-1192, Japan
[9]Department of Pediatrics, National Defense Medical College, Tokorozawa 359-8513, Japan

The Journal of Experimental Medicine

Downloaded from jem.rupress.org on February 12, 2011

**Hyper-IgE syndrome (HIES) is a primary immunodeficiency characterized by recurrent staphylococcal infections and atopic dermatitis associated with elevated serum IgE levels. Although defective differentiation of IL-17–producing CD4+ T cells (Th17) partly accounts for the susceptibility to staphylococcal skin abscesses and pneumonia, the pathogenesis of atopic manifestations in HIES still remains an enigma. In this study, we examined the differentiation and function of Th1, Th2, regulatory T cells ($T_{reg}$ cells), and dendritic cells (DCs) in HIES patients carrying either *STAT3* or *TYK2* mutations. Although the in vitro differentiation of Th1 and Th2 cells and the number and function of $T_{reg}$ cells in the peripheral blood were normal in HIES patients with *STAT3* mutations, primary and monocyte-derived DCs showed defective responses to IL-10 and thus failed to become tolerogenic. When treated with IL-10, patient DCs showed impaired up-regulation of inhibitory molecules on their surface, including PD-L1 and ILT-4, compared with control DCs. Moreover, IL-10–treated DCs from patients displayed impaired ability to induce the differentiation of naive CD4+ T cells to FOXP3+ induced $T_{reg}$ cells ($iT_{reg}$ cells). These results suggest that the defective generation of IL-10–induced tolerogenic DCs and $iT_{reg}$ cells may contribute to inflammatory changes in HIES.**

CORRESPONDENCE
Yoshiyuki Minegishi:
yminegishi.mbch@tmd.ac.jp

Abbreviations used: cDC, conventional DC; DN, dominant-negative; HIES, hyper-IgE syndrome; IPEX, immune dysregulation, polyendocrinopathy, enteropathy, X-linked; $iT_{reg}$ cell, induced $T_{reg}$ cell; MoDC, monocyte-derived DC; mRNA, messenger RNA; $nT_{reg}$ cell, natural $T_{reg}$ cell; pDC, plasmacytoid DC; Q-PCR, quantitative RT-PCR.

Hyper-IgE syndrome (HIES) is a rare complex primary immunodeficiency, characterized by atopic dermatitis, extremely high serum IgE levels, staphylococcal skin abscesses, and pneumonia associated with disproportionately mild inflammatory responses (Grimbacher et al., 2005; Minegishi, 2009). Treatments so far are symptomatic, including the prevention of bacterial and fungal infections and management of eczema. Previous studies suggested the benefit from bone marrow transplantation, Ig replacement, and IFN and G-CSF administration (Grimbacher et al., 2005), but a general role for immune reconstitution and modulation in HIES is unproven. To improve the long-term quality of life of HIES patients, it is necessary to develop a new treatment strategy based on a better understanding of molecular mechanisms of this syndrome. We recently demonstrated that

© 2011 Saito et al. This article is distributed under the terms of an Attribution–Noncommercial–Share Alike–No Mirror Sites license for the first six months after the publication date (see http://www.rupress.org/terms). After six months it is available under a Creative Commons License (Attribution–Noncommercial–Share Alike 3.0 Unported license, as described at http://creativecommons.org/licenses/by-nc-sa/3.0/).

The Rockefeller University Press $30.00
J. Exp. Med.
www.jem.org/cgi/doi/10.1084/jem.20100799

most cases of HIES are caused by dominant-negative (DN) mutations of the *STAT3* gene (Holland et al., 2007; Minegishi et al., 2007). However, the pathogenesis of this syndrome remains unclear. In particular, the molecular mechanisms underlying the allergic manifestations, including atopic dermatitis and extremely high serum IgE levels, remain one of the great enigmas in the pathogenesis of this syndrome.

STAT3 is a transcription factor that binds to the promoter regions of various genes, including those encoding acute-phase proteins. STAT3 plays a critical role in signal transduction for many cytokines, including those of the γc family (IL-2, IL-7, IL-9, IL-15, and IL-21), the gp130 family (IL-6, IL-11, IL-27, and IL-31), the IL-10 family (IL-10 and IL-22), and receptor-type tyrosine kinases. The systemic deletion of STAT3 in mice is lethal, but studies involving the tissue-specific deletion of STAT3 have demonstrated that STAT3 plays a critical role in cell migration, survival, proliferation, apoptosis, inflammation, and tumorigenesis in many tissues (Akira, 2000). Furthermore, recent data unanimously demonstrated that STAT3 plays an essential role for Th17 cell development in humans (de Beaucoudrey et al., 2008; Ma et al., 2008; Milner et al., 2008; Renner et al., 2008; Minegishi et al., 2009), which could explain, at least in part, why HIES patients suffer from recurrent staphylococcal infections confined to the skin and lung (Minegishi et al., 2009).

Allergic diseases may result from an inappropriate balance between effector Th2 cells and $T_{reg}$ cells (Umetsu and DeKruyff, 2006; Akdis and Akdis, 2009; Lloyd and Hawrylowicz, 2009). Th2 cells respond to allergens and produce IL-4, IL-5, IL-9, and IL-13. Th2 cytokines induce changes in blood vessels that lead to the up-regulation of intercellular adhesion molecule 1 and vascular cell-adhesion molecule 1, in turn leading to the recruitment of very late antigen 4–expressing eosinophils. These factors also induce the survival and activation of eosinophils. In addition, IL-4 and IL-13 are responsible for promoting Ig class switching to IgE (Hammad and Lambrecht, 2008). Newly identified cytokines such as IL-25, IL-31, and IL-33 also participate in Th2 cell–mediated inflammation (Dillon et al., 2004; Wang et al., 2007; Kakkar and Lee, 2008). Th1 cells may also contribute to allergic inflammation by inducing the apoptosis of epithelial cells in atopic dermatitis (Trautmann et al., 2000).

$T_{reg}$ cells are key mediators of peripheral tolerance that actively suppress effector T cells and inhibit immune response–mediated tissue damage. Both $FOXP3^+$ $T_{reg}$ cells and IL-10–producing $FOXP3^-$ $T_{reg}$ cells play an essential role in the regulation of allergic inflammation (Curotto de Lafaille et al., 2001; Zheng and Rudensky, 2007; Sakaguchi et al., 2008). There are two types of $FOXP3^+$ $T_{reg}$ cells: natural $T_{reg}$ cells ($nT_{reg}$ cells) and induced $T_{reg}$ cells ($iT_{reg}$ cells). $nT_{reg}$ cells develop in the thymus, whereas $iT_{reg}$ cells develop in the periphery. In the presence of TGF-β1, naive $FOXP3^-$ $CD4^+$ T cells are converted into $FOXP3^+$ $iT_{reg}$ cells (Chen et al., 2003; Coombes et al., 2007; Rubtsov and Rudensky, 2007; Zheng et al., 2007). Mutations in the human *FOXP3* gene result in immune dysregulation, polyendocrinopathy, enteropathy, X-linked (IPEX) syndrome (Bennett et al., 2001; Wildin et al., 2001). Patients with IPEX syndrome suffer from enteropathy, autoimmune diabetes and thyroiditis, food allergy, and atopic dermatitis with extremely high serum IgE levels. FOXP3 deficiency in mice also leads to atopic manifestations (Fontenot et al., 2003; Lin et al., 2005).

DCs are central to the orchestration of the various types of immunity and tolerance (Banchereau et al., 2000; Kapsenberg, 2003; Steinman et al., 2003). Immature DCs function as sentinels in the periphery, undergoing terminal differentiation in response to various danger signals. Maturing DCs migrate to the lymph nodes, where they acquire potent antigen-presenting capacity and induce vigorous T cell responses by expressing co-stimulatory molecules and secreting large amounts of proinflammatory cytokines. The interaction between DCs and naive $CD4^+$ T cells is considered to determine the fate of $CD4^+$ T cells. Cytokines produced by DCs, such as IL-12 and IFN-α, may bias $CD4^+$ T cell priming toward the Th1 pathway (Schulz et al., 2000). Notch ligands, such as Jagged 1, expressed by DCs may promote $CD4^+$ T cells toward the Th2 pathway (Amsen et al., 2009). In addition, DCs play a key role in the induction and maintenance of peripheral T cell tolerance (Steinman et al., 2003; Rutella et al., 2006).

We investigated the molecular mechanism underlying the atopic manifestations in HIES by studying Th1–Th2–$T_{reg}$ cell balance and the development and function of primary and monocyte-derived DCs (MoDCs). The results suggest that IL-10 signaling by DCs may be crucial for the generation of tolerogenic DCs and $iT_{reg}$ cells for the maintenance of an appropriate Th1–Th2–$T_{reg}$ cell balance in vivo in humans.

## RESULTS

### Normal Th1 and Th2 differentiation from naive $CD4^+$ T cells but increased Th2 cytokine production from activated T cells in PBMCs of *STAT3* patients

We first evaluated Th1 and Th2 cell development of naive $CD4^+$ T cells in *STAT3* patients. Naive $CD4^+$ T cells were unstimulated or stimulated with anti-CD3 and anti-CD28 (anti-CD3/CD28) mAbs under neutral, Th1, and Th2 differentiation conditions, and the development of IFN-γ– and IL-4–producing cells was evaluated by cytoplasmic staining and flow cytometry. The development of Th1 and Th2 cells was similar in control subjects and *STAT3* patients (Fig. S1 A). This observation was confirmed by ELISA of the culture supernatants of naive $CD4^+$ T cells, showing similar levels of IFN-γ, IL-5, and IL-13 secretion for control subjects and *STAT3* patients (Fig. S1 B). We next evaluated Th1 and Th2 cytokine production from PBMCs after stimulation with anti-CD3/CD28 mAbs. The production of IFN-γ was equivalent between control subjects and *STAT3* patients, but the production of IL-5 and IL-13 was increased in *STAT3* patients compared with control subjects (Fig. S1 C). These results suggest that cells in PBMCs other than naive $CD4^+$ T cells are likely to be responsible for increased Th2 cytokine production in *STAT3* patients.

Downloaded from jem.rupress.org on February 12, 2011

Published February 7, 2011



### The number and suppressive activity of $T_{reg}$ cells in the peripheral blood are normal in *STAT3* patients

We next evaluated the number of FOXP3$^+$ $T_{reg}$ cells among PBMCs because STAT3 is involved in the transduction of IL-6 and IL-21 signals, which may influence the balance between n$T_{reg}$ cell and Th17 cell differentiation (Harrington et al., 2005; Bettelli et al., 2006; Ivanov et al., 2006; Veldhoen et al., 2006). Similar numbers of PBMCs were obtained from control subjects and *STAT3* patients, and these cells were stained for extracellular CD4 and CD25 and intracellular FOXP3 and evaluated by flow cytometry. The percentages of CD4$^+$CD25$^+$ cells and CD4$^+$FOXP3$^+$ cells did not differ significantly between control subjects and *STAT3* patients (Fig. 1 A).

We then investigated the function of $T_{reg}$ cells in the peripheral blood ex vivo. CD4$^+$CD25$^+$CD62L$^+$ $T_{reg}$ cells were obtained from the peripheral blood of control subjects and *STAT3* patients at a purity of >99% and were co-cultured with autologous CD4$^+$CD25$^-$CD62L$^+$ responder T cells in the presence or absence of anti-CD3/CD28 mAbs. The addition of 1.25 × 10$^3$ control $T_{reg}$ cells to the 1.25 × 10$^4$ control responder T cells resulted in levels of [$^3$H]thymidine incorporation 55% lower than those obtained after the addition of 1.25 × 10$^3$ control responder T cells. Levels of [$^3$H]thymidine incorporation were similarly lowered by the addition of 1.25 × 10$^3$ patient $T_{reg}$ cells to the 1.25 × 10$^4$ patient responder T cells (Fig. 1 B). Modification of the ratio of $T_{reg}$ cells to responder T cells from 1:1 ($T_{reg}$ cell/responder T cell) to 1:100 resulted in no significant difference in the percent suppression of [$^3$H]thymidine incorporation between control subjects and *STAT3* patients (Fig. 1 C). These results indicate that the in vivo generation and ex vivo function of $T_{reg}$ cells were normal in *STAT3* patients.

### Defective IL-10 signaling in MoDCs from *STAT3* patients

We next evaluated the generation of MoDCs in vitro. Isolated CD14$^+$ monocytes from the PBMCs of control subjects and *STAT3* patients were cultured with GM-CSF and IL-4 for 5 d and then allowed to mature in the presence of LPS for 2 d. MoDC differentiation was normal, as shown by evaluations of the forward and side light scatter of the cells (Fig. S2 A), the expression levels of CD1a (Fig. S2 B), CD80, CD83, and CD86 (Fig. S2 C), and FITC-dextran uptake (Fig. S2 D). Of note, levels of CD86 expression before LPS stimulation were slightly higher in *STAT3* patients than in control subjects (Fig. S2 C), suggesting that autocrine IL-10 may regulate the expression of DC maturation markers in control subjects but not in *STAT3* patients (Corinti et al., 2001).

We have previously demonstrated that *STAT3* plays an important role in IL-10 signal transduction in human monocyte-derived macrophages (Minegishi et al., 2007). We therefore investigated IL-10 signal transduction in MoDCs. Consistent with our previous findings, the transcriptional

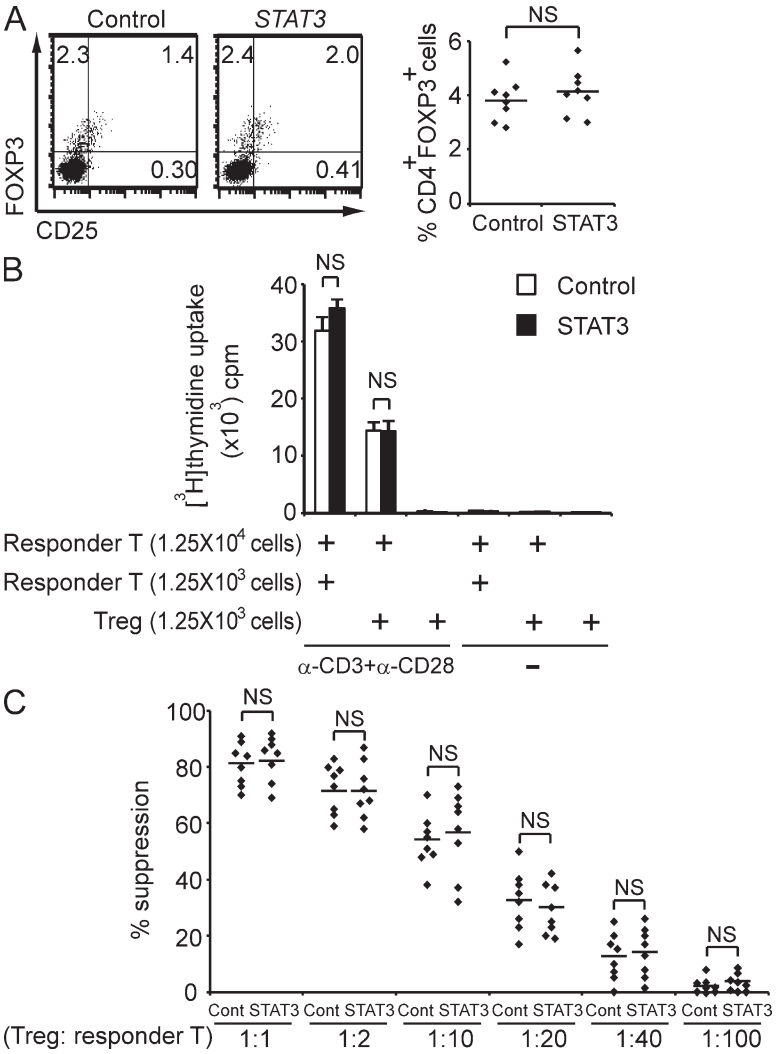


**Figure 1. The number and suppressive activity of $T_{reg}$ cells in the peripheral blood are normal in *STAT3* patients.** (A, left) Representative dot plots gated on CD4$^+$ peripheral blood T cells from a control subject and a *STAT3* patient. (right) Summary data from eight control subjects and eight *STAT3* patients showing percentages of CD4$^+$FOXP3$^+$ cells. Data are representative of at least two independent experiments. (B) CD4$^+$CD25$^-$CD62L$^+$ responder T cells and CD4$^+$CD25$^+$CD62L$^+$ $T_{reg}$ cells were isolated by cell sorting. Responder T cells and $T_{reg}$ cells were co-cultured as indicated for 5 d with or without a 1:100 (vol/vol) dilution of anti-CD3 + anti-CD28 mAb–coated beads. For the evaluation of proliferation, 1 µCi (37 kBq) [$^3$H]thymidine was added to the culture medium for the last 18 h. Graph shows mean ± SD. (C) CD4$^+$CD25$^-$CD62L$^+$ responder T cells and CD4$^+$CD25$^+$CD62L$^+$ $T_{reg}$ cells were isolated and cultured as in B at the indicated ratio. Summary data ($n$ = 8 each) are shown. Data are representative of at least two independent experiments performed in triplicate. (A and C) Horizontal bars indicate mean values.

Downloaded from jem.rupress.org on February 12, 2011

up-regulation of *SOCS3* and *VCAN* (*CSPG2*), two genes responsive to IL-10, was impaired in MoDCs from *STAT3* patients, as demonstrated by comparison with control subjects (Fig. 2 A). Intact signal transduction was observed for TGF-β1, the other critical inhibitory cytokine, in the MoDCs of *STAT3* patients (Fig. S2 E). We evaluated the effect of prior treatment with IL-10 on the phenotypic maturation of MoDCs. IL-10 was added to the culture medium on day 3 of DC differentiation. The prior treatment with IL-10 did not block the differentiation of MoDCs in response to GM-CSF and IL-4 (Fig. S3, A and B) but inhibited the LPS-induced maturation of MoDCs, with inhibition of the up-regulation of co-stimulatory molecules CD80 and CD86 and defective up-regulation of the DC maturation marker CD83 in a control subject. In contrast, the maturation of MoDCs derived from *STAT3* patients showed little sign of inhibition by prior treatment with IL-10 (Fig. S3 C). Up-regulation of CD80, CD83, and CD86 expression by LPS was inhibited by IL-10 pretreatment in control subjects, but the IL-10 pretreatment failed to inhibit the up-regulation of CD80, CD83, and CD86 by LPS in *STAT3* patients (Fig. 2 B). Consistent with this observation, the production of inflammatory cytokines, including TNF, IL-6, and IL-12p40, was suppressed by prior treatment with IL-10 in control subjects. The suppression by IL-10 was severely impaired in the MoDCs from *STAT3* patients (Fig. 2 C). Untreated and IL-10–treated MoDCs were harvested, extensively washed, and co-cultured with third-party allogeneic naive $CD4^+$ T cells from control subjects. LPS-stimulated mature MoDCs induced a significant increase in the uptake of [$^3$H]thymidine by naive $CD4^+$ T cells, with IL-10–treated DCs (IL-10–DCs) from a control subject markedly inhibiting the incorporation of [$^3$H]thymidine. In contrast, the down-regulation was very modest in the IL-10–treated MoDCs from *STAT3* patients. In the absence of MoDCs or naive $CD4^+$ T cells, almost no incorporation of [$^3$H]thymidine was detected (Fig. S4 A). Production of IFN-γ, IL-5, and IL-13 followed a very similar pattern, with prior IL-10 treatment inducing significant down-regulation in control subjects and barely detectable down-regulation in *STAT3* patients (Fig. 2 D). Thus, IL-10 was defective in MoDCs from *STAT3* patients, impairing suppression of (a) the up-regulation of co-stimulatory molecules on MoDCs, (b) the up-regulation of cytokine production by MoDCs, (c) the proliferation of co-cultured naive $CD4^+$ T cells, and (d) cytokine production by co-cultured naive $CD4^+$ T cells.

### IL-10 signaling defect in MoDCs leads to the defective generation of tolerogenic DCs and $iT_{reg}$ cells

Control MoDCs up-regulated the expression of inhibitory molecules, including PD-L1, PD-L2, ILT-3, and ILT-4 but not ICOS-L by IL-10 treatment. The up-regulation of these inhibitory molecules was severely impaired in the MoDCs of *STAT3* patients (Fig. 3 A). We then investigated the functional consequences of the defective up-regulation of inhibitory molecules for MoDCs by co-culturing untreated and IL-10–DCs with third-party allogeneic naive $CD4^+$ T cells from control subjects. *FOXP3* messenger RNA (mRNA) levels in $CD4^+$ T cells co-cultured with control IL-10–DCs were approximately four times higher than those for cells co-cultured with untreated control MoDCs. However, up-regulation was severely impaired when naive $CD4^+$ T cells were co-cultured with IL-10–DCs from *STAT3* patients (Fig. 3 B). This observation was confirmed by the cytoplasmic staining of FOXP3 protein and flow cytometric analysis of the $CD4^+$ T cells (Fig. 3 C). This up-regulation of FOXP3 was not likely to be mediated by simple T cell activation because naive $CD4^+$ T cells cultured with control IL-10–DCs proliferated less vigorously compared with those with control DCs and because naive $CD4^+$ T cells cultured with patient DCs proliferated more vigorously compared with those with control DCs in the absence or presence of pretreatment with IL-10 (Fig. S4 B). $iT_{reg}$ cells from control subjects and *STAT3* patients expressed equivalent amount of CD25 on their surface, but the expression levels of CTLA-4 and GITR (glucocorticoid-induced TNFR-related) were up-regulated by the co-culture with control IL-10–DCs, but the up-regulation was impaired by the co-culture with patient IL-10–DCs (Fig. S5).

We further evaluated the consequences of defective FOXP3 up-regulation by investigating $iT_{reg}$ cell activity. Purified $CD4^+CD25^+$ T cells from the co-culture were added to autologous $CD4^+CD25^-$ responder T cells, and the mixture was stimulated with anti-CD3/CD28 mAbs. $CD4^+CD25^+$ T cells cultured with control IL-10–DCs efficiently suppressed the proliferation of CFSE-labeled autologous responder T cells (Fig. 3 D, left, second panel). The suppression of proliferation was severely impaired by $CD4^+CD25^+$ T cells cultured with patient IL-10–DCs (Fig. 3 D, left, third panel). We further evaluated cytokine production by a co-culture of responder T cells and $CD4^+CD25^+$ T cells. The production of IFN-γ, IL-5, and IL-13 was suppressed by co-culture with $CD4^+CD25^+$ cells cultured with control IL-10–DCs (Fig. 3 E). The cytokine production was rather increased by the addition of $CD4^+CD25^+$ T cells cultured with patient IL-10–DCs, which might be caused by decreased $iT_{reg}$ cells and increased activated T cells in this $CD4^+CD25^+$ T cell population from *STAT3* patients. Thus, the IL-10 signaling defect in MoDCs results in the impaired generation of tolerogenic DCs and $iT_{reg}$ cells.

The generation of $FOXP3^+$ $iT_{reg}$ cells is dependent on TGF-β1 (Chen et al., 2003; Coombes et al., 2007; Rubtsov and Rudensky, 2007; Zheng et al., 2007). We therefore investigated the relationship between IL-10–DCs and TGF-β1 in the generation of $FOXP3^+$ $iT_{reg}$ cells. TGF-β1 in the culture medium efficiently up-regulated FOXP3 expression in naive $CD4^+$ T cells in the presence of untreated immature DCs (Fig. 3 F). Control IL-10–DCs up-regulated FOXP3 expression, equivalent to TGF-β1 (Fig. 3 F, fifth dataset vs. third dataset), and a combination of control IL-10–DCs and TGF-β1 (Fig. 3 F, seventh dataset) further up-regulated FOXP3 expression. TGF-β1 effectively up-regulated FOXP3 expression in naive $CD4^+$ T cells when co-cultured with patient DCs, but patient IL-10–DCs were inefficient for the up-regulation

Downloaded from jem.rupress.org on February 12, 2011

Published February 7, 2011



of FOXP3 expression (Fig. 3 F, sixth dataset). Thus, in addition to TGF-β1, IL-10–DCs play a crucial role in the generation of FOXP3$^+$ iT$_{reg}$ cells. Moreover, these results demonstrated that the defect in FOXP3 up-regulation was not caused by the lack of TGF-β1 in IL-10–DCs from *STAT3* patients because the addition of exogenous TGF-β1 did not rescue this

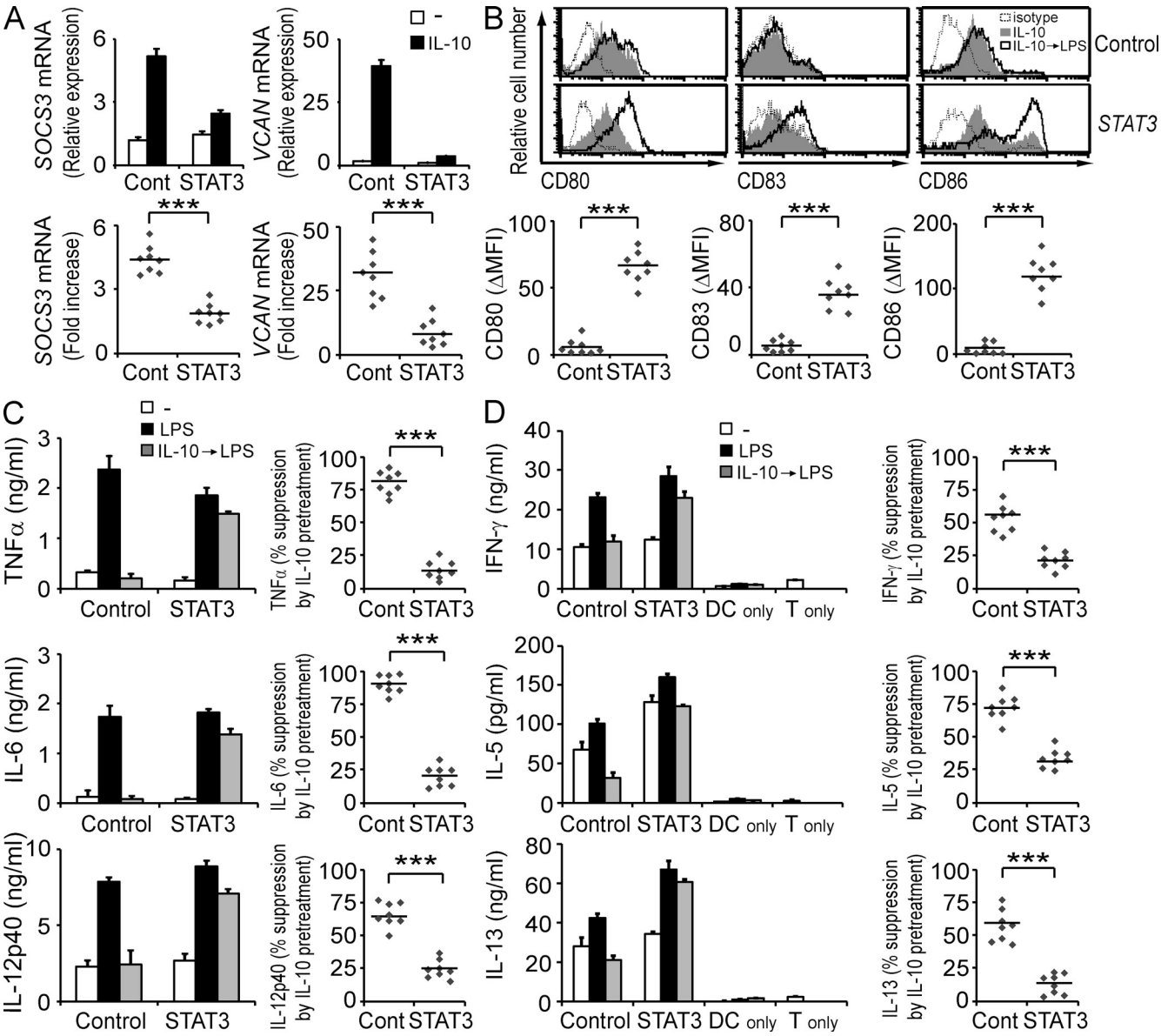


**Figure 2. Defective IL-10 signaling in MoDCs from *STAT3* patients.** (A) Immature DCs from a control subject and a *STAT3* patient were stimulated with or without IL-10 for 2 h, and the amounts of *SOCS3* and *VCAN* (*CSPG2*) mRNAs were analyzed by Q-PCR. The representative data are shown at the top, normalized to *HPRT* levels, with the level of unstimulated control cells defined as 1.0. Summary data ($n$ = 8 each) showing fold increase are at the bottom. Data are representative of at least two independent experiments performed in triplicate. (B) IL-10–treated MoDCs (IL-10–DCs) were generated from CD14$^+$ monocytes by culturing with GM-CSF and IL-4 in the presence of IL-10 from day 3 of the culture. Representative histograms of CD80, CD83, and CD86 expression of IL-10–DCs (IL-10) and LPS-matured MoDCs after prior treatment with IL-10 (IL-10 → LPS) from a control subject and a *STAT3* patient are at the top. Dashed lines indicate staining with isotype-matched control mAbs. Summary data ($n$ = 8 each) showing delta values of mean fluorescence intensity (ΔMFI), LPS-matured IL-10–DCs minus IL-10–DCs, of CD80, CD83, and CD86 are at the bottom. (C) Representative cytokine levels in the culture supernatants of unstimulated immature MoDCs, LPS-matured MoDCs (LPS), and LPS-matured MoDCs after prior treatment with IL-10 (IL-10 → LPS) from a control subject and a *STAT3* patient are on the left. Summary data ($n$ = 8 each) showing percent suppression are on the right. All samples were evaluated in triplicate. (D) Third-party allogeneic naive CD4$^+$ T cells from control subjects were co-cultured with immature DCs (−), LPS-matured DCs (LPS), or LPS-matured DCs after prior treatment with IL-10 (IL-10 → LPS), and the levels of the cytokines were evaluated by ELISA in triplicate. Representative data are on the left, and summary data of percent suppression by IL-10 pretreatment ($n$ = 8 each) are on the right. Data are representative of at least two independent experiments. (A, C, and D) Graphs show mean ± SD. (A–D) Horizontal bars indicate mean values. ***, $P < 0.001$.

Downloaded from jem.rupress.org on February 12, 2011

Published February 7, 2011



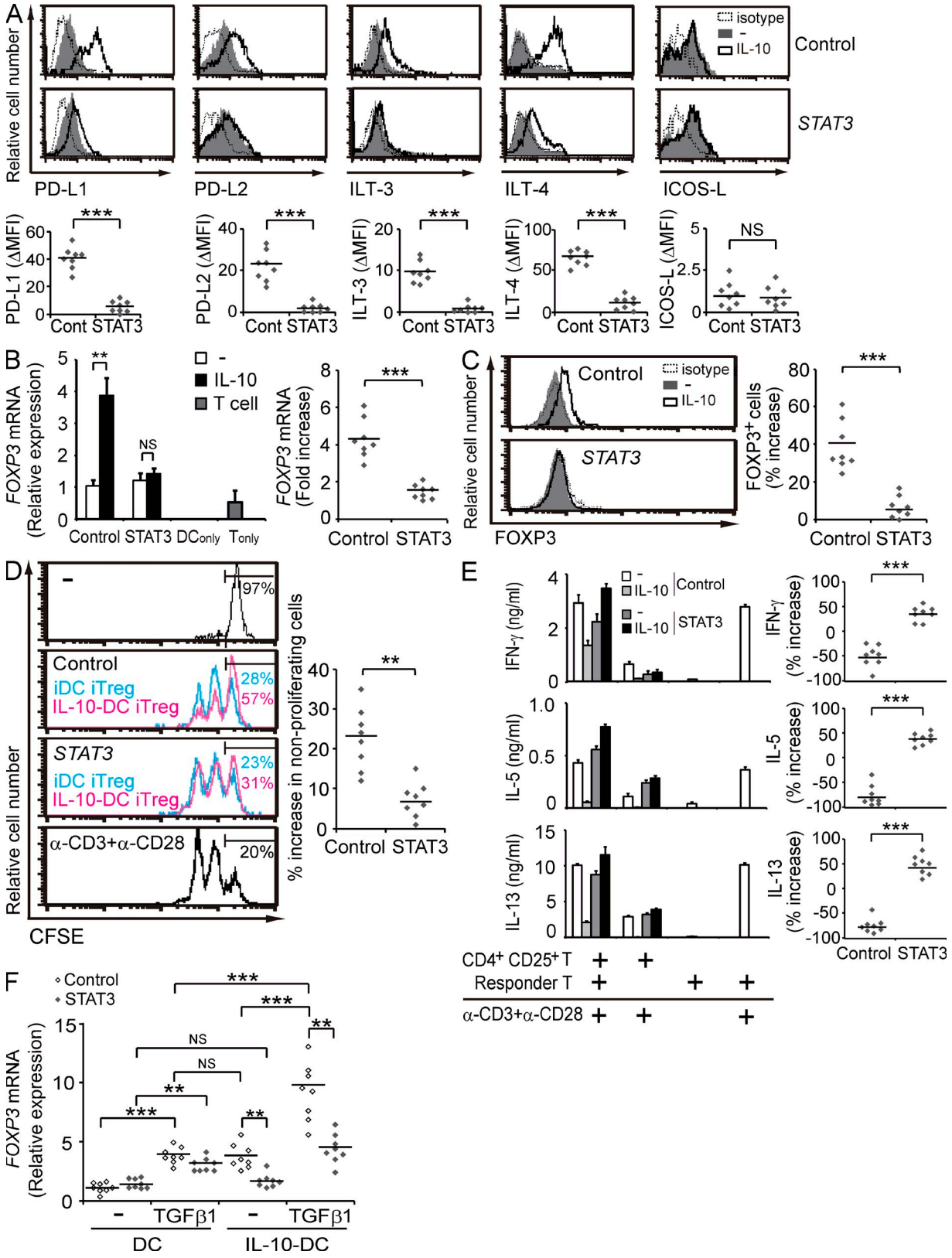


**Figure 3. IL-10 signaling defect in MoDCs leads to the defective generation of tolerogenic DCs and $iT_{reg}$ cells.** (A) Representative histograms showing the levels of PD-L1, PD-L2, ILT-3, ILT-4, and ICOS-L produced by untreated immature MoDCs (−) and IL-10–DCs (IL-10) from a control subject and a *STAT3* patient are shown at the top. Dashed lines indicate staining with isotype-matched control mAbs. Summary data showing ΔMFI,

Downloaded from jem.rupress.org on February 12, 2011

Published February 7, 2011



defect to the level of control IL-10–DCs in the presence of TGF-β1 (Fig. 3 F, eighth dataset vs. seventh dataset). To further clarify, we evaluated TGF-β1 and IL-10 production from MoDCs from control subjects and *STAT3* patients (Fig. S6). These results indicate that the production of these inhibitory cytokines from MoDCs is not impaired in *STAT3* patients.

### PD-L1, ILT-4, and TGF-β1 in response to IL-10–DCs and STAT3 in DCs play a major role in FOXP3 up-regulation

A recent study in mice demonstrated that PD-L1 plays an important role in inducing FOXP3$^+$ iT$_{reg}$ cells (Keir et al., 2008; Francisco et al., 2009). We investigated whether defective PD-L1 expression in IL-10–DCs from *STAT3* patients played a crucial role in the defective generation of FOXP3$^+$ iT$_{reg}$ cells by adding a peptide neutralizing PD-L1 to the co-culture of IL-10–DCs and naive CD4$^+$ T cells. The addition of this PD-L1 peptide significantly decreased the levels of *FOXP3* mRNA in the naive CD4$^+$ T cells co-cultured with control IL-10–DCs (Fig. 4 A). The addition of the neutralizing peptide had no detectable effect on co-cultures with MoDCs from *STAT3* patients.

We next investigated whether defective ILT-4 expression in IL-10–DCs from *STAT3* patients played an important role in the defective generation of FOXP3$^+$ iT$_{reg}$ cells with a neutralizing mAb to the co-culture of IL-10–DCs and naive CD4$^+$ T cells. The addition of anti–ILT-4 mAb significantly down-regulated the levels of *FOXP3* mRNA in the naive CD4$^+$ T cells co-cultured with control IL-10–DCs compared with a control mAb (Fig. 4 B). The addition of the anti–ILT-4 mAb had no significant effect on the co-culture of the naive CD4$^+$ T cells with patient IL-10–DCs. Thus, in addition to PD-L1, ILT-4 up-regulation in response to IL-10 plays an important role in the generation of FOXP3$^+$ iT$_{reg}$ cells.

We further investigated the contribution of TGF-β1 in the up-regulation of FOXP3 by IL-10–DCs because endogenous TGF-β1 may be supplied by the DCs or from the culture medium. The addition of anti–TGF-β1 mAb significantly down-regulated the levels of FOXP3 mRNA in the naive CD4$^+$ T cells co-cultured with control IL-10–DCs compared with a control mAb (Fig. 4 C). The addition of anti–TGF-β1 mAb had no significant effect on the co-culture of naive CD4$^+$ T cells with patient IL-10–DCs. Thus, TGF-β1 is required for the formation of FOXP3$^+$ iT$_{reg}$ cells in response to control IL-10–DCs.

We also investigated whether DN-STAT3 expression in naive CD4$^+$ T cells plays a significant role in the generation of iT$_{reg}$ cells by evaluating the up-regulation of *FOXP3* mRNA levels in naive CD4$^+$ T cells from *STAT3* patients. The up-regulation of *FOXP3* mRNA levels in response to IL-10–DCs from *STAT3* patients was impaired, but naive CD4$^+$ T cells from control subjects and *STAT3* patients up-regulated *FOXP3* mRNA levels in response to control IL-10–DCs (Fig. 4 D). Thus, DN-STAT3 expression in MoDCs plays a major role in the impairment of *FOXP3* mRNA up-regulation, and DN-STAT3 expression in T cells plays, at most, a minor role in *STAT3* patients.

### Primary DCs from *STAT3* patients are defective in IL-10 signaling and up-regulation of PD-L1 and ILT-4

We next investigated the development and function of primary DCs. Two DC subsets were identified in human peripheral blood on the basis of the expression of surface molecules, including CD11c and CD304 (BDCA-4). Lineage marker (Lin) negative HLA-DR$^+$CD11c$^+$CD304$^-$ cells are conventional DCs (cDCs), whereas Lin$^-$HLA-DR$^+$CD11c$^-$CD304$^+$ cells are plasmacytoid DCs (pDCs). The number of PBMCs obtained from the peripheral blood and the percentages of cDCs and pDCs were indistinguishable between control subjects and *STAT3* patients (Fig. 5 A). We next investigated IL-10 signal transduction in primary cDCs and pDCs. The transcriptional up-regulation of *SOCS3* and *VCAN* (*CSPG2*) was impaired in both subsets of primary DCs from *STAT3* patients, as demonstrated by comparison with control subjects (Fig. 5, B and C). We evaluated the effect of prior treatment with IL-10 on the phenotypic maturation of primary cDCs. IL-10 was added to the culture 1 d before LPS treatment, which inhibited the LPS-induced maturation by inhibiting the up-regulation of CD83 and CD86 in control subjects.

Downloaded from jem.rupress.org on February 12, 2011

IL-10–treated minus untreated, of PD-L1, PD-L2, ILT-3, ILT-4, and ICOS-L ($n$ = 8 each) are at the bottom. (B) Q-PCR analysis of *FOXP3* mRNA levels after the co-culture of third-party allogeneic naive CD4$^+$ T cells from a control subject with untreated immature MoDCs (−) or IL-10–DCs (IL-10) from a control subject and a *STAT3* patient. Cultures in the absence of naive CD4$^+$ T cells (DC only) and MoDCs (T only) were used as negative controls. Representative data are on the left, and summary data ($n$ = 8 each) showing fold increase are on the right. (C) Flow cytometric analysis of cytoplasmic FOXP3 protein levels in naive CD4$^+$ T cells co-cultured with untreated immature MoDCs (−) and IL-10–DCs (IL-10) from a control subject and a *STAT3* patient. Staining with isotype-matched control mAbs is indicated by dashed lines. Representative data are on the left, and summary data ($n$ = 8 each) showing percent increase are on the right. (D) CFSE-labeled CD4$^+$CD25$^-$ responder T cells were cultured alone in the absence (−) or presence of anti-CD3 and anti-CD28 mAbs or with iT$_{reg}$ cells generated by co-culture with control or *STAT3* patient immature DCs (iDCs) or IL-10–DCs. After 5 d, the proliferation of CFSE-labeled responder T cells was assessed by flow cytometry. Representative histograms are on the left, and summary data ($n$ = 8 each) showing the percent increase in nonproliferating cells, numbers in magenta minus numbers in blue, are on the right. (E) Cytokine levels in the supernatants of co-cultures of responder T cells and iT$_{reg}$ cells, as indicated. Representative data are on the left, and summary data ($n$ = 8 each) showing percent increase are on the right. Data are representative of at least two independent experiments. (F) Q-PCR analysis of *FOXP3* mRNA expression after the co-culture of third-party allogeneic naive CD4$^+$ T cells from a control subject with untreated immature MoDCs (−) or IL-10–DCs from a control subject and a *STAT3* patient in the absence or presence of exogenous TGF-β1. We show summary data showing relative *FOXP3* expression ($n$ = 8 each) performed in triplicate. Data are representative of at least two independent experiments. (B and E) Graphs show mean ± SD. (A–F) Horizontal bars indicate mean values. **, $P < 0.01$; ***, $P < 0.001$.

Published February 7, 2011



In contrast, the maturation of primary cDCs derived from *STAT3* patients was almost intact by prior treatment with IL-10 (Fig. 5 D). We did not detect inhibitory effects of IL-10 on CD80 up-regulation in control subjects and *STAT3* patients. Furthermore, control primary cDCs up-regulated the expression of inhibitory molecules, including PD-L1, PD-L2, ILT-3 (unpublished data), and ILT-4 by IL-10 treatment. The up-regulation of these inhibitory molecules was impaired in the primary cDCs of *STAT3* patients (Fig. 5 E). These results demonstrate that IL-10 signaling is defective not only in MoDCs but also in primary DCs, resulting in the defective up-regulation of surface inhibitory molecules in *STAT3* patients.

### *TYK2*-deficient MoDCs are also defective in the generation of tolerogenic DCs and $iT_{reg}$ cells

We studied MoDCs from a patient with *TYK2* deficiency to confirm that the IL-10 signaling defect was responsible for the defective generation of tolerogenic DCs and $iT_{reg}$ cells. The absolute numbers of cDCs and pDCs in PBMCs were similar in the *TYK2*-deficient patient and a control subject, and no significant difference in the differentiation of MoDCs was observed on evaluations of forward and side light scatter, CD1a expression, and the expression of CD80, CD83, and CD86 of DCs before and after LPS-induced maturation (Fig. S7, A–D). No inhibition of the up-regulation of CD80, CD83, and CD86 by prior treatment with IL-10 was detectable in cells from the *TYK2*-deficient patient (Fig. 6 A). The up-regulation of PD-L1, PD-L2, ILT-3, and ILT-4 on MoDCs was also defective in the *TYK2*-deficient patient, as shown by comparisons with control subjects (Fig. 6 B). An increase in *FOXP3* mRNA and protein levels was detectable in co-cultures of allogeneic naive $CD4^+$ T cells with control IL-10-DCs but not in co-cultures with *TYK2*-deficient IL-10–DCs (Fig. 6, C and D). Consistent with these observations, no suppression of naive $CD4^+$ T cell proliferation and cytokine production (including IFN-γ, IL-5, and IL-13) was detected when *TYK2*-deficient IL-10–DCs were used

Downloaded from jem.rupress.org on February 12, 2011

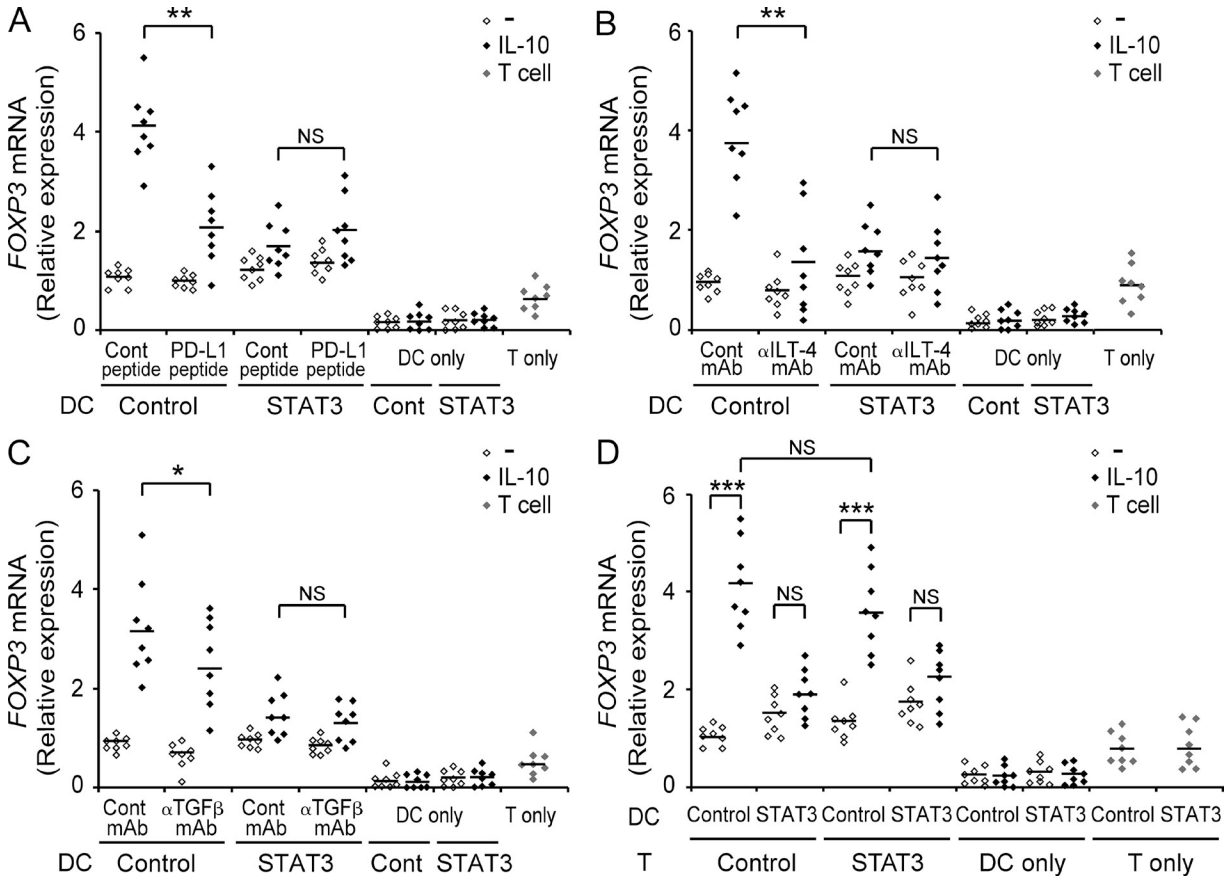


**Figure 4. PD-L1, ILT-4, and TGF-β1 in response to IL-10–DCs and *STAT3* in DCs play a major role in FOXP3 up-regulation.** (A–C) Q-PCR analysis of *FOXP3* mRNA levels in third-party allogeneic naive $CD4^+$ T cells from control (Cont) subjects co-cultured with untreated immature MoDCs (−) and IL-10–DCs (IL-10) from eight control subjects and eight *STAT3* patients. A neutralizing PD-L1 peptide or a control peptide (A), control or ILT-4–neutralizing mAb (B), or control or TGF-β–neutralizing mAb (C) was added where indicated. (D) Q-PCR analysis of *FOXP3* mRNA levels in third-party allogeneic naive $CD4^+$ T cells from control subjects and *STAT3* patients co-cultured with untreated immature DCs (−) or IL-10–DCs (IL-10) from control subjects and *STAT3* patients. Summary data show relative *FOXP3* mRNA expression ($n = 8$ each) and were performed in triplicate. Data are representative of at least two independent experiments. (A–D) Horizontal bars indicate mean values. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

Published February 7, 2011



(Fig. 6, E and F). MoDCs from the *TYK2*-deficient patient produced an equivalent amount of TGF-β1 and reduced amount of IL-10 compared with a control subject, which might be associated with the fact that the type I IFN signal is impaired in the *TYK2*-deficient patient but not in *STAT3* patients.(Fig. S7, E and F). Thus, the IL-10 signaling defect in HIES patients, *STAT3* patients, and the *TYK2*-deficient patient results in the impaired generation of tolerogenic DCs and $iT_{reg}$ cells.

## DISCUSSION

We found that the Th1 and Th2 differentiation of naive $CD4^+$ T cells and the suppressive activity of $T_{reg}$ cells were normal in *STAT3* patients. Recent data have shown that Ig isotype switching in B cells is normal in *STAT3* patients (Avery et al., 2010). Thus, it is not likely that T cell– and B cell–intrinsic mechanisms are responsible for the allergic manifestations in HIES patients. We then investigated DCs, which can regulate the immune response and tolerance. IL-10 signal transduction was defective in the primary DCs and MoDCs of patients, despite the intact TGF-β1 signal transduction in these cells. This defect resulted in impairment of the suppression of cytokine production and T cell proliferation by IL-10–DCs. The generation and suppressive activity of $FOXP3^+$ $iT_{reg}$ cells cultured with IL-10–DCs was impaired in HIES patients. The defective generation of tolerogenic DCs and $iT_{reg}$ cells in response to IL-10 was also observed in the other type of HIES, *TYK2* deficiency. These results suggest that IL-10 signaling in DCs may be crucial for the generation of tolerogenic DCs and $iT_{reg}$ cells to maintain an appropriate Th1–Th2–$T_{reg}$ cell balance in HIES patients.

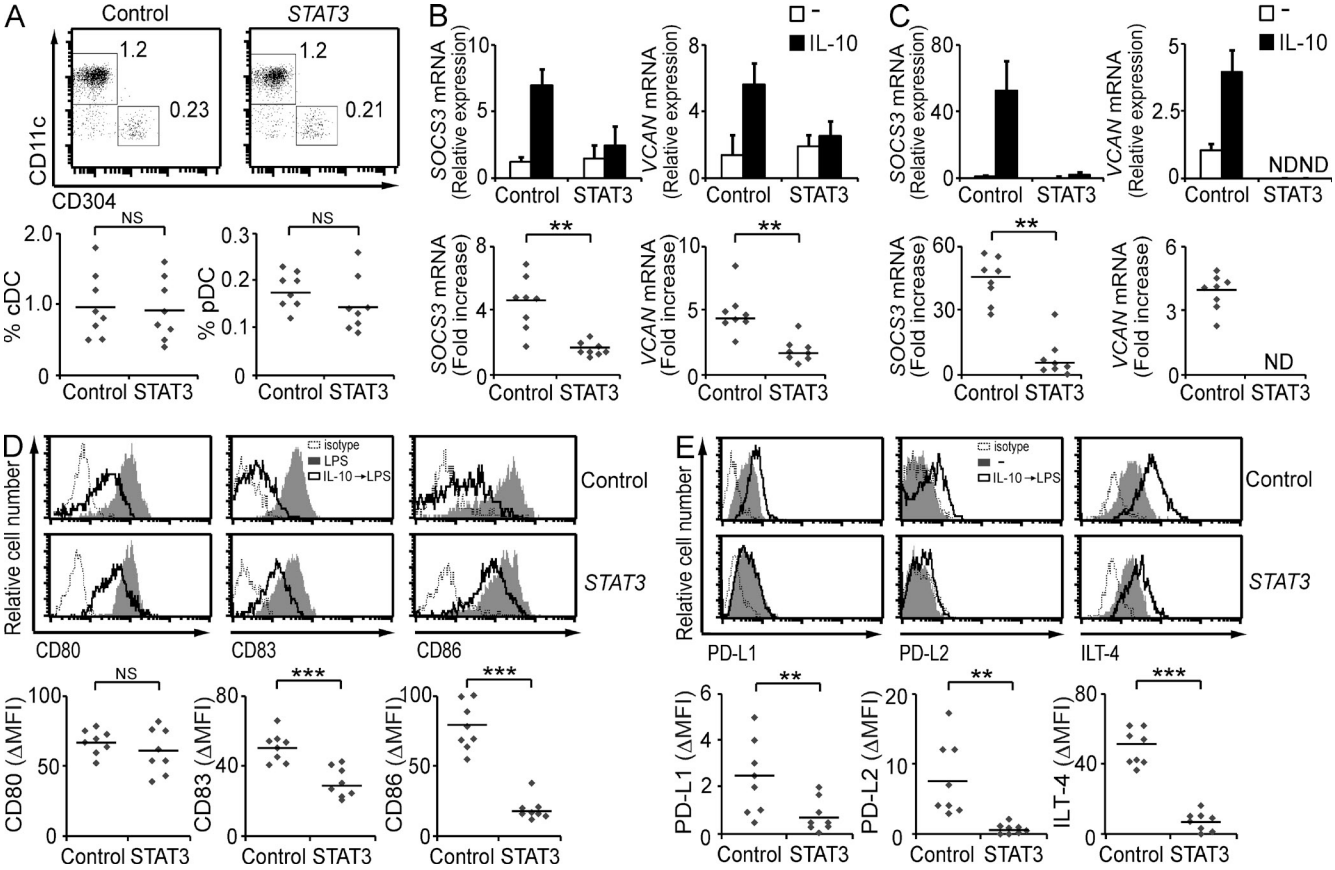


**Figure 5. Primary DCs are defective in IL-10 signal and up-regulation of PD-L1 and ILT-4.** (A) Dot blots are gated on Lin-negative HLA-DR–positive cells from a control subject and a *STAT3* patient. cDCs are $CD11c^+CD304^-$ (BDCA-4), and pDCs are $CD11c^-CD304^+$. Representative dot plots from a control subject and a *STAT3* patient are shown at the top, and pooled data ($n$ = 8 each) showing percentages of cDCs and pDCs are at the bottom. (B and C) Primary cDCs (B) and pDCs (C) from a control subject and a *STAT3* patient were stimulated with IL-10 for 2 h, and the amounts of *SOCS3* and *VCAN* (*CSPG2*) mRNAs were analyzed by Q-PCR. Representative data are shown at the top, normalized to *HPRT* levels, with the level of unstimulated control cells defined as 1.0. Summary data ($n$ = 8 each) showing fold increase are at the bottom. Data are representative of at least two independent experiments performed in triplicate. Graphs show mean ± SD. (D) Representative histograms of CD80, CD83, and CD86 expression on control and *STAT3* cDCs stimulated with LPS alone or LPS after IL-10 treatment. Dashed lines indicate staining with isotype-matched control mAbs. Summary data showing ΔMFI, LPS stimulated minus LPS-stimulated IL-10–DCs, ($n$ = 8 each) are at the bottom. (E) Representative histograms of PD-L1, PD-L2, and ILT-4 expression of primary cDCs (−) and IL-10–treated (IL-10) primary cDCs from a control subject and a *STAT3* patient are shown at the top. Summary data ($n$ = 8 each) showing ΔMFI, IL-10 treated minus untreated, of PD-L1, PD-L2, and ILT-4 are shown at the bottom. Data are representative of at least two independent experiments. (A–E) Horizontal bars indicate mean values. **, $P < 0.01$; ***, $P < 0.001$.

Downloaded from jem.rupress.org on February 12, 2011

Published February 7, 2011



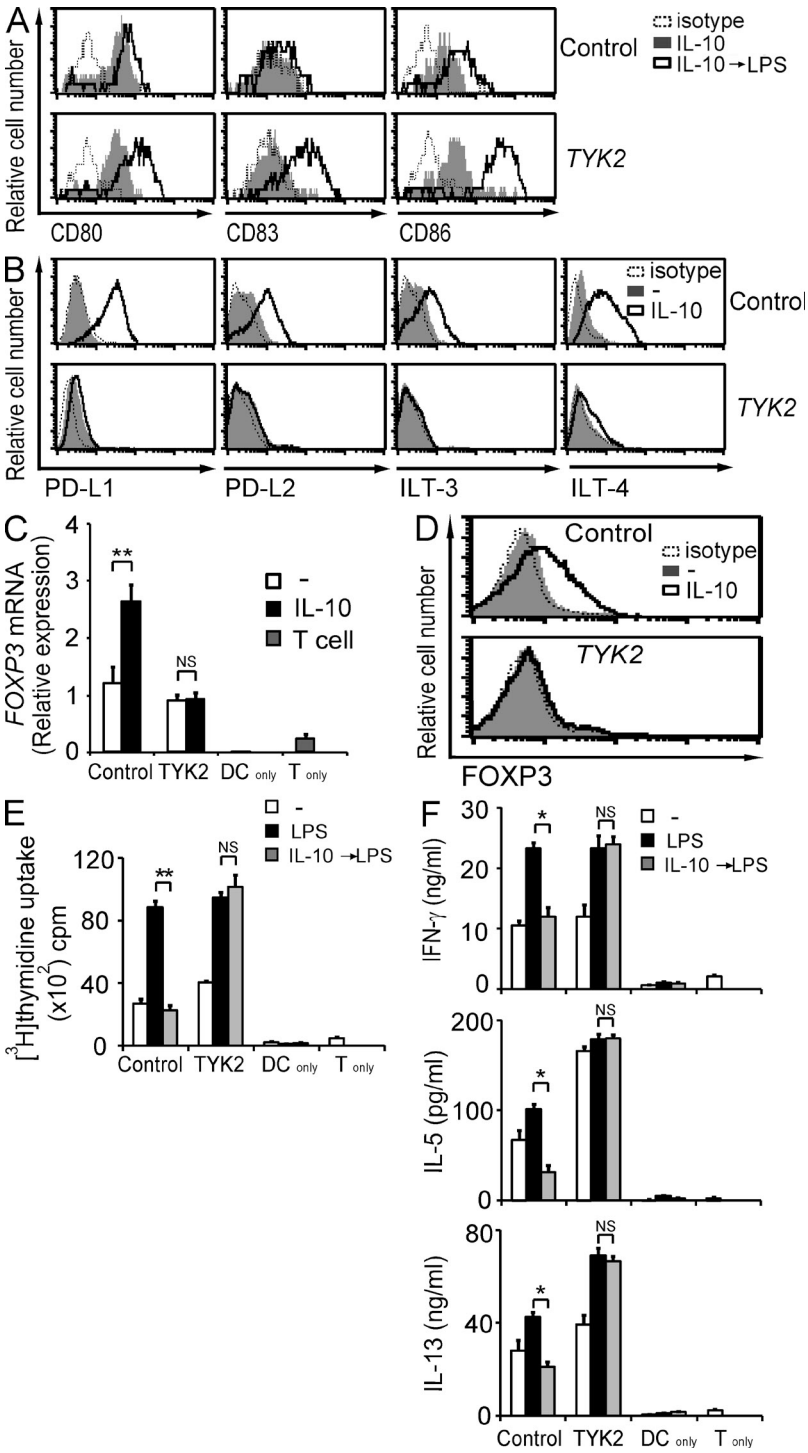


**Figure 6. *TYK2*-deficient MoDCs display defective generation of tolerogenic DCs and $iT_{reg}$ cells.** (A) Flow cytometric analysis of the CD80, CD83, and CD86 expression on IL-10–DCs (IL-10) and LPS-matured MoDCs after prior treatment with IL-10 (IL-10 → LPS), with cells obtained from a control subject and a patient with *TYK2* deficiency. We show representative histograms from three independent experiments. (B) Flow cytometric analysis of the levels of PD-L1, PD-L2, ILT-3, and ILT-4 in untreated immature MoDCs (−) and IL-10–DCs (IL-10) from a control subject and a *TYK2* deficiency. We show representative histograms from three independent experiments. (C) Q-PCR analysis of *FOXP3* mRNA levels after the co-culture of third-party allogeneic naive $CD4^+$ T cells from a control subject with untreated immature MoDCs (−) or IL-10–DCs (IL-10) from a control subject and a *TYK2*-deficient patient. We show representative data from three independent experiments. (D) Flow cytometric analysis of cytoplasmic FOXP3 protein levels in untreated immature MoDCs (−) and IL-10–DCs (IL-10) from a control subject and a *TYK2*-deficient patient. Isotype-matched control (isotype) antibody staining is indicated by a dashed line. We show representative histograms from three independent experiments. (E) Third-party allogeneic naive $CD4^+$ T cells from control subjects were co-cultured with immature MoDCs (−), LPS-matured MoDCs (LPS), or LPS-matured MoDCs after prior treatment with IL-10 (IL-10 → LPS). The cells were obtained from a control subject and a *TYK2*-deficient patient. After 5 d, proliferation was evaluated by pulsing the cells with 1 μCi (37 kBq) [$^3$H]thymidine for the final 18 h of culture. All samples were evaluated in triplicate. We show representative data from three independent experiments. (F) Cells were cultured as in E, and cytokine levels were evaluated as indicated. All samples were evaluated in triplicate. We show representative data from at least three independent experiments. (C, E, and F) Graphs show mean ± SD. *, $P < 0.05$; **, $P < 0.01$.

The exposure of the skin to allergens induces allergen-specific unresponsiveness, possibly because of the production of IL-10 by keratinocytes (Enk and Katz, 1992; Enk et al., 1993). Langerhans cells and dermal DCs receive IL-10 signal and induce allergen-specific tolerance. This defect in IL-10–mediated tolerance to innocuous environmental antigens may be one of the mechanisms underlying the allergic signs in HIES patients. In humans, we are not certain about the $nT_{reg}$ cell/$iT_{reg}$ cell ratio in the peripheral blood under resting conditions. Our data suggest that most of the $T_{reg}$ cells in the peripheral blood are $nT_{reg}$ cells, which are derived from the thymus and are independent of the IL-10 signal. $iT_{reg}$ cells in the peripheral blood may be a minor population under resting conditions but may play a crucial role in the regulation of antigen-specific allergic reactions.

Human peripheral blood $T_{reg}$ cells suppressed proliferation and Th2 cytokine production by responder T cells stimulated with allergens (Bellinghausen et al., 2003; Grindebacke et al., 2004; Ling et al., 2004). $CD4^+$ T cells cultured with IL-10–DCs have antigen-specific $iT_{reg}$ cell activity (Steinbrink et al., 2002). In vitro experiments suggested that the suppression is dependent on cell to cell contact between $iT_{reg}$ cells and responder T cells and is not mediated by soluble factors. In this study, we found that the generation of $FOXP3^+$ $iT_{reg}$ cells by

Downloaded from jem.rupress.org on February 12, 2011

Published February 7, 2011



IL-10–DCs was impaired in HIES patients. Evidence is accumulating to suggest that interactions between tolerogenic DCs and $T_{reg}$ cells play an important role in the maintenance of immune tolerance against self-antigens and innocuous environmental antigens (Yamazaki et al., 2006a; Hubert et al., 2007). $CD4^+CD25^+$ $T_{reg}$ cell populations can expand in the presence of DCs with intact suppressive activity in vitro and in vivo (Yamazaki et al., 2006b). In addition to the IL-10 signal provided by the cells sensing innocuous environmental antigens, the IL-10–mediated positive feedback loop between tolerogenic DCs and $iT_{reg}$ cells is probably impaired in HIES patients, and this may also constitute one of the mechanisms underlying the atopic signs in HIES patients.

A large number of clinical studies have demonstrated that IL-10 is involved in the molecular pathogenesis of atopic disorders in humans. The frequency of allergen-specific, IL-10–secreting T cells is significantly higher in nonatopic individuals than in atopic patients (Akdis et al., 2004). IL-10 levels are inversely correlated with the severity of human allergic diseases (Borish et al., 1996; Lim et al., 1998). Furthermore, allergen-specific immunotherapies increase IL-10 synthesis by T cells (Francis et al., 2003; Vissers et al., 2004). All of these findings suggest that IL-10 plays a key role in the control of atopic diseases in humans.

In contrast, mice lacking IL-10 or the IL-10 receptor develop spontaneous inflammation in the large intestine (Kühn et al., 1993; Davidson et al., 1996; Spencer et al., 1998). Mice with a $T_{reg}$ cell–specific IL-10 deficiency also display inflammation of surfaces in contact with the environment such as the colon, lungs, and skin (Rubtsov et al., 2008). In humans, mutations in the genes encoding IL-10 receptor subunits have been found in patients with early-onset enterocolitis (Glocker et al., 2009). Thus, a lack of IL-10 signaling results in enterocolitis in both humans and mice. Interestingly, in patients with HIES, immune responses to innocuous environmental antigens are limited to the skin, with no marked increase in the frequency of enterocolitis. One possible reason for this discrepancy is the existence of a partial, as opposed to complete, IL-10 signaling deficiency in *STAT3* patients, creating a situation resembling $T_{reg}$ cell–specific IL-10 deficiency. An alternative nonmutually exclusive explanation is that, in addition to the IL-10 signaling defect, *STAT3* patients have defective Th17 cell development (de Beaucoudrey et al., 2008; Ma et al., 2008; Milner et al., 2008; Renner et al., 2008; Minegishi et al., 2009). The combination of Th17 cell deficiency and IL-10 signaling may result in allergic signs but prevent the development of enterocolitis (Brand, 2009).

$T_{reg}$ cells mediate peripheral tolerance and play a central role in determining several immunopathologies, including autoimmunity, chronic infections, tumor development, and allergies (Hawrylowicz and O'Garra, 2005). $FOXP3^+$ $T_{reg}$ cells are involved in protecting humans against allergic diseases, as patients with IPEX syndrome suffer from allergic symptoms (Bennett et al., 2001; Wildin et al., 2001). PBMCs from atopic patients proliferate more extensively and produce more Th2 cytokines in response to allergens than do PBMCs from nonatopic healthy individuals (Taams et al., 2002; Ling et al., 2004). However, patients with atopic dermatitis have normal numbers of $T_{reg}$ cells in the periphery with normal suppressive activity (Ou et al., 2004). These results suggest that $iT_{reg}$ cells may be more important than $nT_{reg}$ cells in controlling atopic dermatitis. Consistent with this hypothesis, a recent study using two mouse strains, one capable of generating $iT_{reg}$ cells but incapable of generating $nT_{reg}$ cells and the other unable to generate either $iT_{reg}$ or $nT_{reg}$ cells, suggested that $iT_{reg}$ cells controlled allergic inflammation against innocuous environmental allergens, whereas $nT_{reg}$ cells did not (Curotto de Lafaille et al., 2008).

TGF-β1 is the other crucial inhibitory cytokine regulating lymphocyte homeostasis, inhibiting Th1 and Th2 cell responses and promoting the differentiation of $iT_{reg}$ cells (Li et al., 2006). One previous study suggested that STAT3 might be involved in transduction of the TGF-β1 signal (Ohkawara et al., 2004), but we detected no impairment of TGF-β1 signaling in DCs from *STAT3* patients. Unexpectedly, we found that TGF-β1 and IL-10–DCs operated synergistically to up-regulate FOXP3 expression in naive $CD4^+$ T cells. This suggests that the defective generation of IL-10–DCs may have a far-reaching impact on the induction of $iT_{reg}$ cells in HIES patients.

We provide in this study the first demonstration that an IL-10 signaling defect leads to the impairment of tolerogenic DC and $iT_{reg}$ cell production in the HIES. These results suggest that the defect in tolerogenic DC and $iT_{reg}$ cell production, even in the presence of normal $nT_{reg}$ cells, may contribute to the development of complex clinical manifestations, including allergic inflammation in HIES patients. Furthermore, a unique combination of defective Th17 differentiation and $iT_{reg}$ cell generation may culminate in the development of atopic dermatitis but not enterocolitis in HIES patients.

## MATERIALS AND METHODS

**Patients.** All *STAT3* patients enrolled in this study had typical clinical findings associated with HIES and a National Institutes of Health score >40 points (Table I; Grimbacher et al., 1999). The diagnosis was confirmed by the identification of mutations in the *STAT3* gene. The patient with *TYK2* deficiency has been described elsewhere (Minegishi et al., 2006). The study was approved by the Tokyo Medical and Dental University Ethics Committee, and written informed consent was obtained from all patients. Control individuals were nonatopic, age-matched, and equivalent in sex distribution to HIES patients. All of the patients and control subjects were in a healthy state when their blood samples were collected.

**Antibodies, cytokines, and peptides.** We used mAbs against CD4 (RPA-T4), CD14 (M5E2), CD11c (B-ly6), CD123 (9F5), HLA-DR (TU36), CD25 (M-A251), CD62L (Dreg 56), CD1a, (HI149), CD80 (L307.4), CD86 (2331), CD83 (HB15e), PD-L1 (MIH1), PD-L2 (MIH18), FOXP3 (259D/C7), and CTLA-4 (CD152; BNI3), a Lin cocktail (antibodies against CD3 [SK7], CD14 [MΦP9], CD16 [3G8], CD19 [SJ25C1], CD20 [L27], and CD56 [NCAM16.2]), and mAbs against IFN-γ (4S.B3) and IL-4 (8D4-8), neutralizing mAbs against IFN-γ (B27), IL-4 (MP4-25D2), and isotype-matched control mAbs, all of which were purchased from BD. We obtained antibodies against ILT-3 (CD85K; 293623), ILT-4 (CD85d; 287219), LAP (latency-associated peptide; TGF-β1; 27235), and GITR (TNFRSF18; 110416) from R&D Systems. Anti–ICOS-L antibody (MIH12) was obtained from eBioscience. Anti-CD304 (BDCA-4) antibody (AD5-17F6) was obtained

Downloaded from jem.rupress.org on February 12, 2011

**Table I.** Characteristics of HIES patients

| Patient | Age | Sex | Mutation | Domain | Highest IgE | NIH score | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Total points | Skin abscess | Pneumonia | Eosino philia | Newborn rash | Eczema | URI | Candidiasis | Serious infection | Lung abnormality | Face | Nasal width | Retained teeth | Scoliosis | Fracture | Hyperex tensibility | High palate |
| | *yr* | | | | *IU/ml* | | | | | | | | | | | | | | | | | |
| STAT3-1 | 23 | F | ΔV463 | DNA binding | 17,500 | 58 | 2 | 8 | 0 | 4 | 2 | 0 | 0 | 0 | 8 | 5 | 3 | 8 | 4 | 0 | 4 | 0 |
| STAT3-2 | 11 | F | R382W | DNA binding | 97,900 | 66 | 8 | 8 | 6 | 4 | 4 | 2 | 1 | 0 | 8 | 2 | 1 | 8 | 0 | 0 | 4 | 0 |
| STAT3-3 | 24 | M | ΔV463 | DNA binding | 62,000 | 56 | 8 | 0 | 6 | 4 | 4 | 0 | 4 | 4 | 8 | 5 | 1 | 0 | 0 | 0 | 0 | 2 |
| STAT3-4 | 13 | M | R382Q | DNA binding | 11,600 | 41 | 8 | 8 | 0 | 4 | 4 | 0 | 0 | 4 | 0 | 2 | 1 | 0 | 0 | 0 | 0 | 0 |
| STAT3-5 | 16 | F | H437Y | DNA binding | 50,600 | 44 | 8 | 4 | 6 | 4 | 4 | 0 | 0 | 0 | 0 | 5 | 3 | 0 | 0 | 0 | 0 | 0 |
| STAT3-6 | 23 | F | S636F | SH2 | 25,400 | 68 | 8 | 8 | 0 | 4 | 2 | 2 | 4 | 0 | 6 | 5 | 3 | 8 | 0 | 4 | 4 | 0 |
| STAT3-7 | 49 | F | G618D | SH2 | 21,300 | 53 | 8 | 8 | 0 | 4 | 4 | 0 | 0 | 4 | 8 | 2 | 1 | 0 | 0 | 4 | 0 | 0 |
| STAT3-8 | 34 | M | Δ371-380 | DNA binding | 12,300 | 53 | 8 | 0 | 0 | 4 | 4 | 0 | 4 | 4 | 0 | 5 | 3 | 1 | 0 | 4 | 4 | 2 |
| TYK2-1 | 23 | M | Frame shift | NA | 2,100 | 48 | 8 | 8 | 3 | 4 | 4 | 2 | 1 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

NA, not applicable. Possible HIES patients are evaluated by the National Institutes of Health (NIH) scoring system. If the total points of NIH score are >40 points, the patient is considered as HIES clinically. NIH score is defined as follows. If the highest serum IgE level is >2,000 IU/ml, the patient scores 10 points. Skin abscess: 8 points indicate more than four, and 2 points indicate one or two episodes of skin abscess in lifetime. Pneumonia: 8 points indicate more than three, and 4 points indicate two episodes of pneumonia in lifetime. Eosinophilia: 6 points indicate >800 eosinophils/μl, and 3 points indicate 700–800 eosinophils/μl of blood (700/μl = 1 SD and 800/μl = 2 SD above the mean value from normal individuals). Newborn rash: 4 points indicate newborn rash is present. Eczema: 4 points indicate eczema is severe, and 2 points indicate eczema is moderate in worst stage. Upper respiratory infections (URI): 2 points indicate the patient sufferers from upper respiratory infections six to four times, 1 point indicates three times per year. Candidiasis: 4 points indicate the patient has systemic candidiasis, and 1 point indicates oral candidiasis. Serious infections: 8 points indicate the patient has episodes of fatal and serious infection, and 4 points indicate the patient has an episode of serious infection. Lung abnormality: 8 points indicate the patient has pneumatocele, and 6 points indicate the patient has bronchiectasis. Face: 5 points indicate the patient has typical characteristic facial appearance, and 2 points indicate mild characteristic facial appearance. Nasal width: 3 points indicate the patient has nasal width of >2 SD, and 1 point indicates nasal width with 1–2 SD. Retained teeth: 8 points indicate the patient has more than three retained primary teeth, and 1 point indicates the patient has one retained primary tooth. Scoliosis: 4 points indicate the patient has scoliosis of 15–20°, and 2 points indicate scoliosis of 10–14°. Fracture: 4 points indicate the patient has one or two episodes of fracture with minor trauma. Hyperextensibility: 4 points indicate the patient has hyperextensible joints. High palate: 2 points indicate the patient has a high palate. In all items, 0 points indicate the finding is absent. None of the patients have lymphoma or midline anomaly.



Downloaded from jem.rupress.org on February 12, 2011

Published February 7, 2011



from Miltenyi Biotec. Recombinant human (rh) GM-CSF, IL-4, IFN-γ, IL-10, and TGF-β1 were purchased from PeproTech. Neutralizing PD-L1 peptide was obtained from Abcam, and an irrelevant peptide was used as a negative control.

**PBMCs and naive CD4+ T cell culture.** PBMCs were isolated by Ficoll density gradient centrifugation (Histopaque-1077; Sigma-Aldrich). PBMCs were cultured in 96-well plates in RPMI 1640 medium supplemented with 10% fetal bovine serum, 200 mM L-glutamine, 100 mM sodium pyruvate, nonessential amino acids, minimal essential medium vitamins (all from Invitrogen), 50 U/50 μg/ml penicillin/streptomycin (Nacalai Tesque), and 50 μM mercaptoethanol. Cultures were stimulated with a 1:100 (vol/vol) dilution of anti-CD3/CD28 mAb–coated beads from Invitrogen. For some experiments, the following mAbs and cytokines were added: 10 ng/ml rhIFN-γ, 10 ng/ml rhIL-4, and neutralizing antibodies against 10 μg/ml IFN-γ and 10 μg/ml IL-4.

**$T_{reg}$ cell purification and functional assay.** Total $CD4^+$ T cells were isolated with the $CD4^+$ T cell isolation kit (BD). The cells were stained for sorting with antibodies against CD4, CD25, and CD62L. All mAbs were used after dialysis to remove sodium azide (Baecher-Allan et al., 2006). $CD4^+CD25^-CD62L^{hi}$ responder T cells and $CD4^+CD25^+CD62L^{hi}$ $T_{reg}$ cell populations were isolated by sorting with a cell sorter (Moflo; Beckman Coulter). In the postsort analysis, the resulting cell preparation was found to be to >99% purity. Co-culture was set up as follows: $1.25 \times 10^4$ responder T cells and $1.25 \times 10^3$ $T_{reg}$ cells were co-cultured for 5 d with a 1:100 (vol/vol) dilution of magnetic beads coated with antibodies against CD3/CD28. Responder T cells were used as a negative control. Proliferation was assessed by adding 1 μCi (37 kBq) [$^3$H]thymidine (methyl-[$^3$H]thymidine; ICN Biomedicals) to the culture medium for the final 18 h.

**Isolation of primary DCs.** Primary DCs were obtained by the enrichment using a human DC enrichment set (BD) and cell sorting with FACS Aria II (BD): cDCs as $Lin^-HLA\text{-}DR^+$ $CD11c^+CD304^-$ cells and pDCs as $Lin^-HLA\text{-}DR^+CD11c^-CD304^+$ cells. In the postsort analysis, the resulting cell preparation was to >99% purity.

**In vitro generation of MoDCs.** $CD14^+$ monocytes were isolated from PBMCs with immunomagnetic beads (BD) at a purity of >98%. Monocytes were cultured in the presence of 50 ng/ml GM-CSF and 10 ng/ml IL-4 for 5 d. For differentiation into mature DCs, immature DCs were stimulated on day 5 with 100 ng/ml LPS (O55:B5; Sigma-Aldrich). For the generation of tolerogenic DCs, 100 ng/ml IL-10 was added to the culture on day 3. Nonadherent DCs on day 7 were used for T cell stimulation.

**Allogeneic naive CD4+ T cell proliferation assay.** Naive $CD4^+$ T cells were negatively selected from PBMCs through the depletion of CD8, CD11b, CD16, CD19, CD36, CD41a, CD45RO, CD56, CD123, γδ-TCR, and glycophorin A–positive cells, with antibody-coated paramagnetic microbeads (naive $CD4^+$ T cell isolation kit from BD), according to the manufacturer's protocol. The purity of the naive $CD4^+$ T cell preparation exceeded 95%. For proliferation assays, $10^5$ naive $CD4^+$ T cells were co-cultured in 96-well round-bottomed plates, in triplicate, with $10^4$ allogeneic DCs. After 5 d, the cells were pulsed with 1 μCi (37 kBq) per well of [$^3$H]thymidine for 18 h, and [$^3$H]thymidine incorporation was evaluated with a β counter (model 1450; PerkinElmer).

**$iT_{reg}$ cell preparation and functional evaluation.** Naive $CD4^+$ T cells were obtained from PBMCs with the naive $CD4^+$ T cell isolation kit. We obtained $CD4^+CD25^-$ responder T cells by depleting the $CD25^+$ cells with magnetic beads coated with an antibody against CD25 (BD). The resulting cell preparation was >95% pure. We obtained $iT_{reg}$ cells by setting up co-cultures as described for the Allogeneic naive $CD4^+$ T cell proliferation assay and purifying $CD4^+CD25^+$ cells after 3 d with immunomagnetic beads. $CD4^+CD25^+$ $iT_{reg}$ cells were co-cultured with CFSE-labeled autologous $CD4^+CD25^-$ responder T cells in 96-well round-bottomed plates containing a 1:100 (vol/vol) dilution of anti-CD3/CD28 mAb beads. After 5 d, the proliferation of the CFSE-labeled $CD4^+CD25^-$ T cells was assessed by flow cytometry.

**Flow cytometric analysis.** Cells were analyzed on a FACSCalibur or FACSCanto II machine (BD) using CellQuest or FACSDiva software (BD).

**Mannose receptor–mediated endocytosis.** 1 mg/ml FITC–dextran (Sigma-Aldrich) was incubated with $10^5$ cells at 37°C or 4°C for 2 h. FITC-dextran uptake was stopped by adding ice-cold PBS, and the cells were then thoroughly washed in a refrigerated centrifuge. Samples were then subjected to flow cytometry. The level of antigen uptake by DCs was assessed as the difference between the test (37°C) and control (4°C) values for each sample.

**Cytokine ELISA.** For cytokine determinations, the culture supernatant was stored at −80°C until use, and the amounts of IFN-γ, TNF, IL-5, IL-6, IL-10, IL-12p40, and IL-13 present were then determined by ELISA, according to the kit manufacturer's instructions (BD).

**Intracellular staining.** Naive $CD4^+$ T cells were cultured with plate-bound antibodies against CD3 and CD28 in Th1 conditions, IFN-γ plus antibody against IL-4 in Th2 conditions, or IL-4 and antibody against IFN-γ, and the cells were then fixed and permeabilized (Cytofix/Cytoperm reagents; BD) and stained with mAbs against CD4, IFN-γ, and IL-4, according to the manufacturer's instructions (BD). CTLA-4 staining was performed after Cytofix/Cytoperm treatment.

**FOXP3 intracellular staining.** Naive $CD4^+$ T cells co-cultured with untreated DCs or IL-10–DCs were fixed and permeabilized with the human FOXP3 buffer set (BD) and stained with mAb against FOXP3.

**RNA isolation and real-time quantitative RT-PCR (Q-PCR).** Cells were harvested for total RNA isolation with the Fastpure RNA kit (Takara Bio Inc.). Total RNA was reverse transcribed with Primescript RT (Takara Bio Inc.). An aliquot of the RT products was used as a template for real-time PCR with SYBR green Mastermix (Takara Bio Inc.) on an Mx3005P thermocycler (Agilent Technologies) with SYBR green I dye as the amplicon detector and ROX as the passive reference. The gene for HPRT (hypoxanthine phosphoribosyltransferase) was amplified as an endogenous reference. Quantification was achieved by both the standard curve and comparative ΔΔCT methods.

**Data analysis.** Data are expressed as means ± the SD. Unpaired *t* tests or analysis of variance was used for statistical analysis. P-values <0.05 were considered significant (*, $P < 0.05$; **, $P < 0.01$; and ***, $P < 0.001$).

**Online supplemental material.** Fig. S1 shows normal Th1 and Th2 differentiation from naive $CD4^+$ T cells but increased Th2 cytokine production from activated T cells in PBMCs of *STAT3* patients. Fig. S2 shows that MoDC differentiation in vitro and TGF-β1 signaling in MoDCs are intact in *STAT3* patients. Fig. S3 shows that IL-10 treatment does not impair the differentiation of MoDCs, but down-regulation of CD80, CD83, and CD86 is defective in MoDCs from *STAT3* patients. Fig. S4 shows that suppression of proliferation by IL-10 pretreatment is impaired in MoDCs from *STAT3* patients. Fig. S5 shows that up-regulation of FOXP3, CTLA-4, and GITR is impaired in $iT_{reg}$ cells co-cultured with patient IL-10–DCs. Fig. S6 shows that MoDCs from *STAT3* patients produce equivalent amounts of TGF-β1. Fig. S7 shows the characterization of primary DCs and MoDCs from the patient with *TYK2* deficiency. Online supplemental material is available at http://www.jem.org/cgi/content/full/jem.20100799/DC1.

We thank Ms. S. Miyakoshi for assistance with cell sorting with Moflo.

This work is supported by Grants-in-Aid from the Japanese Ministry of Education, Culture, Sports, Science and Technology (22021015 and 22390205),

Downloaded from jem.rupress.org on February 12, 2011

Japan Science and Technology Agency, Core Research for Evolutional Science and Technology, Research on Intractable Diseases from the Ministry of Health, Labour and Welfare, the Uehara Foundation, the Naito Foundation, the Takeda Science Foundation, and the Mitsubishi Foundation.

The authors have no conflicting financial interests.

**Submitted: 22 April 2010**
**Accepted: 11 January 2011**

## REFERENCES

Akdis, C.A., and M. Akdis. 2009. Mechanisms and treatment of allergic disease in the big picture of regulatory T cells. *J. Allergy Clin. Immunol.* 123:735–746. doi:10.1016/j.jaci.2009.02.030

Akdis, M., J. Verhagen, A. Taylor, F. Karamloo, C. Karagiannidis, R. Crameri, S. Thunberg, G. Deniz, R. Valenta, H. Fiebig, et al. 2004. Immune responses in healthy and allergic individuals are characterized by a fine balance between allergen-specific T regulatory 1 and T helper 2 cells. *J. Exp. Med.* 199:1567–1575. doi:10.1084/jem.20032058

Akira, S. 2000. Roles of STAT3 defined by tissue-specific gene targeting. *Oncogene*. 19:2607–2611. doi:10.1038/sj.onc.1203478

Amsen, D., A. Antov, and R.A. Flavell. 2009. The different faces of Notch in T-helper-cell differentiation. *Nat. Rev. Immunol.* 9:116–124. doi:10.1038/nri2488

Avery, D.T., E.K. Deenick, C.S. Ma, S. Suryani, N. Simpson, G.Y. Chew, T.D. Chan, U. Palendira, J. Bustamante, S. Boisson-Dupuis, et al. 2010. B cell–intrinsic signaling through IL-21 receptor and STAT3 is required for establishing long-lived antibody responses in humans. *J. Exp. Med.* 207:155–171. doi:10.1084/jem.20091706

Baecher-Allan, C., E. Wolf, and D.A. Hafler. 2006. MHC class II expression identifies functionally distinct human regulatory T cells. *J. Immunol.* 176:4622–4631.

Banchereau, J., F. Briere, C. Caux, J. Davoust, S. Lebecque, Y.J. Liu, B. Pulendran, and K. Palucka. 2000. Immunobiology of dendritic cells. *Annu. Rev. Immunol.* 18:767–811. doi:10.1146/annurev.immunol.18.1.767

Bellinghausen, I., B. Klostermann, J. Knop, and J. Saloga. 2003. Human CD4+CD25+ T cells derived from the majority of atopic donors are able to suppress TH1 and TH2 cytokine production. *J. Allergy Clin. Immunol.* 111:862–868. doi:10.1067/mai.2003.1412

Bennett, C.L., J. Christie, F. Ramsdell, M.E. Brunkow, P.J. Ferguson, L. Whitesell, T.E. Kelly, F.T. Saulsbury, P.F. Chance, and H.D. Ochs. 2001. The immune dysregulation, polyendocrinopathy, enteropathy, X-linked syndrome (IPEX) is caused by mutations of FOXP3. *Nat. Genet.* 27:20–21. doi:10.1038/83713

Bettelli, E., Y. Carrier, W. Gao, T. Korn, T.B. Strom, M. Oukka, H.L. Weiner, and V.K. Kuchroo. 2006. Reciprocal developmental pathways for the generation of pathogenic effector TH17 and regulatory T cells. *Nature*. 441:235–238. doi:10.1038/nature04753

Borish, L., A. Aarons, J. Rumbyrt, P. Cvietusa, J. Negri, and S. Wenzel. 1996. Interleukin-10 regulation in normal subjects and patients with asthma. *J. Allergy Clin. Immunol.* 97:1288–1296. doi:10.1016/S0091-6749(96)70197-5

Brand, S. 2009. Crohn's disease: Th1, Th17 or both? The change of a paradigm: new immunological and genetic insights implicate Th17 cells in the pathogenesis of Crohn's disease. *Gut*. 58:1152–1167. doi:10.1136/gut.2008.163667

Chen, W., W. Jin, N. Hardegen, K.J. Lei, L. Li, N. Marinos, G. McGrady, and S.M. Wahl. 2003. Conversion of peripheral $CD4^+CD25^-$ naive T cells to $CD4^+CD25^+$ regulatory T cells by TGF-β induction of transcription factor *Foxp3*. *J. Exp. Med.* 198:1875–1886. doi:10.1084/jem.20030152

Coombes, J.L., K.R. Siddiqui, C.V. Arancibia-Cárcamo, J. Hall, C.M. Sun, Y. Belkaid, and F. Powrie. 2007. A functionally specialized population of mucosal $CD103^+$ DCs induces $Foxp3^+$ regulatory T cells via a TGF-β– and retinoic acid–dependent mechanism. *J. Exp. Med.* 204:1757–1764. doi:10.1084/jem.20070590

Corinti, S., C. Albanesi, A. la Sala, S. Pastore, and G. Girolomoni. 2001. Regulatory activity of autocrine IL-10 on dendritic cell functions. *J. Immunol.* 166:4312–4318.

Curotto de Lafaille, M.A., S. Muriglan, M.J. Sunshine, Y. Lei, N. Kutchukhidze, G.C. Furtado, A.K. Wensky, D. Olivares-Villagómez, and J.J. Lafaille. 2001. Hyper immunoglobulin E response in mice with monoclonal populations of B and T lymphocytes. *J. Exp. Med.* 194:1349–1359. doi:10.1084/jem.194.9.1349

Curotto de Lafaille, M.A., N. Kutchukhidze, S. Shen, Y. Ding, H. Yee, and J.J. Lafaille. 2008. Adaptive Foxp3+ regulatory T cell-dependent and -independent control of allergic inflammation. *Immunity*. 29:114–126. doi:10.1016/j.immuni.2008.05.010

Davidson, N.J., M.W. Leach, M.M. Fort, L. Thompson-Snipes, R. Kühn, W. Müller, D.J. Berg, and D.M. Rennick. 1996. T helper cell 1-type CD4+ T cells, but not B cells, mediate colitis in interleukin 10-deficient mice. *J. Exp. Med.* 184:241–251. doi:10.1084/jem.184.1.241

de Beaucoudrey, L., A. Puel, O. Filipe-Santos, A. Cobat, P. Ghandil, M. Chrabieh, J. Feinberg, H. von Bernuth, A. Samarina, L. Jannière, et al. 2008. Mutations in STAT3 and IL12RB1 impair the development of human IL-17-producing T cells. *J. Exp. Med.* 205:1543–1550. doi:10.1084/jem.20080321

Dillon, S.R., C. Sprecher, A. Hammond, J. Bilsborough, M. Rosenfeld-Franklin, S.R. Presnell, H.S. Haugen, M. Maurer, B. Harder, J. Johnston, et al. 2004. Interleukin 31, a cytokine produced by activated T cells, induces dermatitis in mice. *Nat. Immunol.* 5:752–760. doi:10.1038/ni1084

Enk, A.H., and S.I. Katz. 1992. Early molecular events in the induction phase of contact sensitivity. *Proc. Natl. Acad. Sci. USA*. 89:1398–1402. doi:10.1073/pnas.89.4.1398

Enk, A.H., V.L. Angeloni, M.C. Udey, and S.I. Katz. 1993. Inhibition of Langerhans cell antigen-presenting function by IL-10. A role for IL-10 in induction of tolerance. *J. Immunol.* 151:2390–2398.

Fontenot, J.D., M.A. Gavin, and A.Y. Rudensky. 2003. Foxp3 programs the development and function of CD4+CD25+ regulatory T cells. *Nat. Immunol.* 4:330–336. doi:10.1038/ni904

Francis, J.N., S.J. Till, and S.R. Durham. 2003. Induction of IL-10+ CD4+CD25+ T cells by grass pollen immunotherapy. *J. Allergy Clin. Immunol.* 111:1255–1261. doi:10.1067/mai.2003.1570

Francisco, L.M., V.H. Salinas, K.E. Brown, V.K. Vanguri, G.J. Freeman, V.K. Kuchroo, and A.H. Sharpe. 2009. PD-L1 regulates the development, maintenance, and function of induced regulatory T cells. *J. Exp. Med.* 206:3015–3029. doi:10.1084/jem.20090847

Glocker, E.O., D. Kotlarz, K. Boztug, E.M. Gertz, A.A. Schäffer, F. Noyan, M. Perro, J. Diestelhorst, A. Allroth, D. Murugan, et al. 2009. Inflammatory bowel disease and mutations affecting the interleukin-10 receptor. *N. Engl. J. Med.* 361:2033–2045. doi:10.1056/NEJMoa0907206

Grimbacher, B., A.A. Schäffer, S.M. Holland, J. Davis, J.I. Gallin, H.L. Malech, T.P. Atkinson, B.H. Belohradsky, R.H. Buckley, F. Cossu, et al. 1999. Genetic linkage of hyper-IgE syndrome to chromosome 4. *Am. J. Hum. Genet.* 65:735–744. doi:10.1086/302547

Grimbacher, B., S.M. Holland, and J.M. Puck. 2005. Hyper-IgE syndromes. *Immunol. Rev.* 203:244–250. doi:10.1111/j.0105-2896.2005.00228.x

Grindebacke, H., K. Wing, A.C. Andersson, E. Suri-Payer, S. Rak, and A. Rudin. 2004. Defective suppression of Th2 cytokines by CD4CD25 regulatory T cells in birch allergics during birch pollen season. *Clin. Exp. Allergy*. 34:1364–1372. doi:10.1111/j.1365-2222.2004.02067.x

Hammad, H., and B.N. Lambrecht. 2008. Dendritic cells and epithelial cells: linking innate and adaptive immunity in asthma. *Nat. Rev. Immunol.* 8:193–204. doi:10.1038/nri2275

Harrington, L.E., R.D. Hatton, P.R. Mangan, H. Turner, T.L. Murphy, K.M. Murphy, and C.T. Weaver. 2005. Interleukin 17-producing CD4+ effector T cells develop via a lineage distinct from the T helper type 1 and 2 lineages. *Nat. Immunol.* 6:1123–1132. doi:10.1038/ni1254

Hawrylowicz, C.M., and A. O'Garra. 2005. Potential role of interleukin-10-secreting regulatory T cells in allergy and asthma. *Nat. Rev. Immunol.* 5:271–283. doi:10.1038/nri1589

Holland, S.M., F.R. DeLeo, H.Z. Elloumi, A.P. Hsu, G. Uzel, N. Brodsky, A.F. Freeman, A. Demidowich, J. Davis, M.L. Turner, et al. 2007. STAT3 mutations in the hyper-IgE syndrome. *N. Engl. J. Med.* 357:1608–1619. doi:10.1056/NEJMoa073687

Hubert, P., N. Jacobs, J.H. Caberg, J. Boniver, and P. Delvenne. 2007. The cross-talk between dendritic and regulatory T cells: good or evil? *J. Leukoc. Biol.* 82:781–794. doi:10.1189/jlb.1106694

Ivanov, I.I., B.S. McKenzie, L. Zhou, C.E. Tadokoro, A. Lepelley, J.J. Lafaille, D.J. Cua, and D.R. Littman. 2006. The orphan nuclear receptor RORgammat directs the differentiation program of proinflammatory IL-17+ T helper cells. *Cell*. 126:1121–1133. doi:10.1016/j.cell.2006.07.035

Downloaded from jem.rupress.org on February 12, 2011

Published February 7, 2011




Kakkar, R., and R.T. Lee. 2008. The IL-33/ST2 pathway: therapeutic target and novel biomarker. *Nat. Rev. Drug Discov.* 7:827–840. doi:10.1038/nrd2660

Kapsenberg, M.L. 2003. Dendritic-cell control of pathogen-driven T-cell polarization. *Nat. Rev. Immunol.* 3:984–993. doi:10.1038/nri1246

Keir, M.E., M.J. Butte, G.J. Freeman, and A.H. Sharpe. 2008. PD-1 and its ligands in tolerance and immunity. *Annu. Rev. Immunol.* 26:677–704. doi:10.1146/annurev.immunol.26.021607.090331

Kühn, R., J. Löhler, D. Rennick, K. Rajewsky, and W. Müller. 1993. Interleukin-10-deficient mice develop chronic enterocolitis. *Cell.* 75:263–274. doi:10.1016/0092-8674(93)80068-P

Li, M.O., Y.Y. Wan, S. Sanjabi, A.K. Robertson, and R.A. Flavell. 2006. Transforming growth factor-beta regulation of immune responses. *Annu. Rev. Immunol.* 24:99–146. doi:10.1146/annurev.immunol.24.021605.090737

Lim, S., E. Crawley, P. Woo, and P.J. Barnes. 1998. Haplotype associated with low interleukin-10 production in patients with severe asthma. *Lancet.* 352:113. doi:10.1016/S0140-6736(98)85018-6

Lin, W., N. Truong, W.J. Grossman, D. Haribhai, C.B. Williams, J. Wang, M.G. Martín, and T.A. Chatila. 2005. Allergic dysregulation and hyperimmunoglobulinemia E in Foxp3 mutant mice. *J. Allergy Clin. Immunol.* 116:1106–1115. doi:10.1016/j.jaci.2005.08.046

Ling, E.M., T. Smith, X.D. Nguyen, C. Pridgeon, M. Dallman, J. Arbery, V.A. Carr, and D.S. Robinson. 2004. Relation of CD4+CD25+ regulatory T-cell suppression of allergen-driven T-cell activation to atopic status and expression of allergic disease. *Lancet.* 363:608–615. doi:10.1016/S0140-6736(04)15592-X

Lloyd, C.M., and C.M. Hawrylowicz. 2009. Regulatory T cells in asthma. *Immunity.* 31:438–449. doi:10.1016/j.immuni.2009.08.007

Ma, C.S., G.Y. Chew, N. Simpson, A. Priyadarshi, M. Wong, B. Grimbacher, D.A. Fulcher, S.G. Tangye, and M.C. Cook. 2008. Deficiency of Th17 cells in hyper IgE syndrome due to mutations in *STAT3*. *J. Exp. Med.* 205:1551–1557. doi:10.1084/jem.20080218

Milner, J.D., J.M. Brenchley, A. Laurence, A.F. Freeman, B.J. Hill, K.M. Elias, Y. Kanno, C. Spalding, H.Z. Elloumi, M.L. Paulson, et al. 2008. Impaired T(H)17 cell differentiation in subjects with autosomal dominant hyper-IgE syndrome. *Nature.* 452:773–776. doi:10.1038/nature06764

Minegishi, Y. 2009. Hyper-IgE syndrome. *Curr. Opin. Immunol.* 21:487–492. doi:10.1016/j.coi.2009.07.013

Minegishi, Y., M. Saito, T. Morio, K. Watanabe, K. Agematsu, S. Tsuchiya, H. Takada, T. Hara, N. Kawamura, T. Ariga, et al. 2006. Human tyrosine kinase 2 deficiency reveals its requisite roles in multiple cytokine signals involved in innate and acquired immunity. *Immunity.* 25:745–755. doi:10.1016/j.immuni.2006.09.009

Minegishi, Y., M. Saito, S. Tsuchiya, I. Tsuge, H. Takada, T. Hara, N. Kawamura, T. Ariga, S. Pasic, O. Stojkovic, et al. 2007. Dominant-negative mutations in the DNA-binding domain of STAT3 cause hyper-IgE syndrome. *Nature.* 448:1058–1062. doi:10.1038/nature06096

Minegishi, Y., M. Saito, M. Nagasawa, H. Takada, T. Hara, S. Tsuchiya, K. Agematsu, M. Yamada, N. Kawamura, T. Ariga, et al. 2009. Molecular explanation for the contradiction between systemic Th17 defect and localized bacterial infection in hyper-IgE syndrome. *J. Exp. Med.* 206:1291–1301. doi:10.1084/jem.20082767

Ohkawara, B., K. Shirakabe, J. Hyodo-Miura, R. Matsuo, N. Ueno, K. Matsumoto, and H. Shibuya. 2004. Role of the TAK1-NLK-STAT3 pathway in TGF-beta-mediated mesoderm induction. *Genes Dev.* 18:381–386. doi:10.1101/gad.1166904

Ou, L.S., E. Goleva, C. Hall, and D.Y. Leung. 2004. T regulatory cells in atopic dermatitis and subversion of their activity by superantigens. *J. Allergy Clin. Immunol.* 113:756–763. doi:10.1016/j.jaci.2004.01.772

Renner, E.D., S. Rylaarsdam, S. Anover-Sombke, A.L. Rack, J. Reichenbach, J.C. Carey, Q. Zhu, A.F. Jansson, J. Barboza, L.F. Schimke, et al. 2008. Novel signal transducer and activator of transcription 3 (STAT3) mutations, reduced T(H)17 cell numbers, and variably defective STAT3 phosphorylation in hyper-IgE syndrome. *J. Allergy Clin. Immunol.* 122:181–187. doi:10.1016/j.jaci.2008.04.037

Rubtsov, Y.P., and A.Y. Rudensky. 2007. TGFbeta signalling in control of T-cell-mediated self-reactivity. *Nat. Rev. Immunol.* 7:443–453. doi:10.1038/nri2095

Rubtsov, Y.P., J.P. Rasmussen, E.Y. Chi, J. Fontenot, L. Castelli, X. Ye, P. Treuting, L. Siewe, A. Roers, W.R. Henderson Jr., et al. 2008. Regulatory T cell-derived interleukin-10 limits inflammation at environmental interfaces. *Immunity.* 28:546–558. doi:10.1016/j.immuni.2008.02.017

Rutella, S., S. Danese, and G. Leone. 2006. Tolerogenic dendritic cells: cytokine modulation comes of age. *Blood.* 108:1435–1440. doi:10.1182/blood-2006-03-006403

Sakaguchi, S., T. Yamaguchi, T. Nomura, and M. Ono. 2008. Regulatory T cells and immune tolerance. *Cell.* 133:775–787. doi:10.1016/j.cell.2008.05.009

Schulz, O., A.D. Edwards, M. Schito, J. Aliberti, S. Manickasingham, A. Sher, and C. Reis e Sousa. 2000. CD40 triggering of heterodimeric IL-12 p70 production by dendritic cells in vivo requires a microbial priming signal. *Immunity.* 13:453–462. doi:10.1016/S1074-7613(00)00045-5

Spencer, S.D., F. Di Marco, J. Hooley, S. Pitts-Meek, M. Bauer, A.M. Ryan, B. Sordat, V.C. Gibbs, and M. Aguet. 1998. The orphan receptor CRF2-4 is an essential subunit of the interleukin 10 receptor. *J. Exp. Med.* 187:571–578. doi:10.1084/jem.187.4.571

Steinbrink, K., E. Graulich, S. Kubsch, J. Knop, and A.H. Enk. 2002. CD4(+) and CD8(+) anergic T cells induced by interleukin-10-treated human dendritic cells display antigen-specific suppressor activity. *Blood.* 99:2468–2476. doi:10.1182/blood.V99.7.2468

Steinman, R.M., D. Hawiger, and M.C. Nussenzweig. 2003. Tolerogenic dendritic cells. *Annu. Rev. Immunol.* 21:685–711. doi:10.1146/annurev.immunol.21.120601.141040

Taams, L.S., M. Vukmanovic-Stejic, J. Smith, P.J. Dunne, J.M. Fletcher, F.J. Plunkett, S.B. Ebeling, G. Lombardi, M.H. Rustin, J.W. Bijlsma, et al. 2002. Antigen-specific T cell suppression by human CD4+CD25+ regulatory T cells. *Eur. J. Immunol.* 32:1621–1630. doi:10.1002/1521-4141(200206)32:6<1621::AID-IMMU1621>3.0.CO;2-Q

Trautmann, A., M. Akdis, D. Kleemann, F. Altznauer, H.U. Simon, T. Graeve, M. Noll, E.B. Bröcker, K. Blaser, and C.A. Akdis. 2000. T cell-mediated Fas-induced keratinocyte apoptosis plays a key pathogenetic role in eczematous dermatitis. *J. Clin. Invest.* 106:25–35. doi:10.1172/JCI9199

Umetsu, D.T., and R.H. DeKruyff. 2006. The regulation of allergy and asthma. *Immunol. Rev.* 212:238–255. doi:10.1111/j.0105-2896.2006.00413.x

Veldhoen, M., R.J. Hocking, C.J. Atkins, R.M. Locksley, and B. Stockinger. 2006. TGFbeta in the context of an inflammatory cytokine milieu supports de novo differentiation of IL-17-producing T cells. *Immunity.* 24:179–189. doi:10.1016/j.immuni.2006.01.001

Vissers, J.L., B.C. van Esch, G.A. Hofman, M.L. Kapsenberg, F.R. Weller, and A.J. van Oosterhout. 2004. Allergen immunotherapy induces a suppressive memory response mediated by IL-10 in a mouse asthma model. *J. Allergy Clin. Immunol.* 113:1204–1210. doi:10.1016/j.jaci.2004.02.041

Wang, Y.H., P. Angkasekwinai, N. Lu, K.S. Voo, K. Arima, S. Hanabuchi, A. Hippe, C.J. Corrigan, C. Dong, B. Homey, et al. 2007. IL-25 augments type 2 immune responses by enhancing the expansion and functions of TSLP-DC–activated Th2 memory cells. *J. Exp. Med.* 204:1837–1847. doi:10.1084/jem.20070406

Wildin, R.S., F. Ramsdell, J. Peake, F. Faravelli, J.L. Casanova, N. Buist, E. Levy-Lahad, M. Mazzella, O. Goulet, L. Perroni, et al. 2001. X-linked neonatal diabetes mellitus, enteropathy and endocrinopathy syndrome is the human equivalent of mouse scurfy. *Nat. Genet.* 27:18–20. doi:10.1038/83707

Yamazaki, S., K. Inaba, K.V. Tarbell, and R.M. Steinman. 2006a. Dendritic cells expand antigen-specific Foxp3+ CD25+ CD4+ regulatory T cells including suppressors of alloreactivity. *Immunol. Rev.* 212:314–329. doi:10.1111/j.0105-2896.2006.00422.x

Yamazaki, S., M. Patel, A. Harper, A. Bonito, H. Fukuyama, M. Pack, K.V. Tarbell, M. Talmor, J.V. Ravetch, K. Inaba, and R.M. Steinman. 2006b. Effective expansion of alloantigen-specific Foxp3+ CD25+ CD4+ regulatory T cells by dendritic cells during the mixed leukocyte reaction. *Proc. Natl. Acad. Sci. USA.* 103:2758–2763. doi:10.1073/pnas.0510606103

Zheng, S.G., J. Wang, P. Wang, J.D. Gray, and D.A. Horwitz. 2007. IL-2 is essential for TGF-beta to convert naive CD4+CD25- cells to CD25+Foxp3+ regulatory T cells and for expansion of these cells. *J. Immunol.* 178:2018–2027.

Zheng, Y., and A.Y. Rudensky. 2007. Foxp3 in control of the regulatory T cell lineage. *Nat. Immunol.* 8:457–462. doi:10.1038/ni1455


Downloaded from jem.rupress.org on February 12, 2011

The Journal of Experimental Medicine

## SUPPLEMENTAL MATERIAL

**Saito et al., http://www.jem.org/cgi/content/full/jem.20100799/DC1**

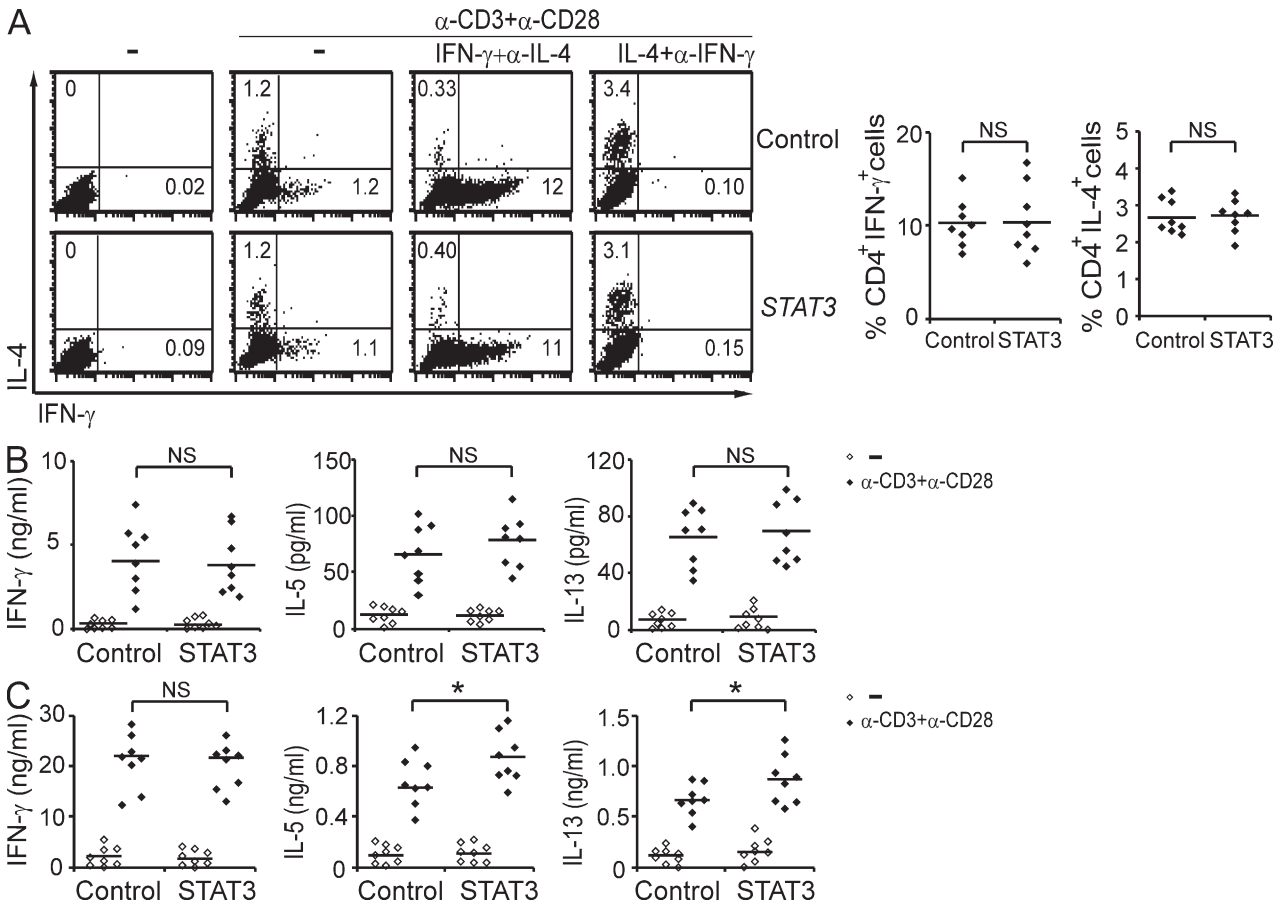


**Figure S1. Normal Th1 and Th2 differentiation from naive CD4+ T cells but increased Th2 cytokine production from activated T cells in PBMCs of *STAT3* patients.** (A) Intracellular staining with mAbs against IFN-γ and IL-4 was performed on naive CD4+ T cells from control subjects and *STAT3* patients either left unstimulated or stimulated with mAbs against CD3 and anti-CD28, alone or in combination with IFN-γ and anti–IL-4 mAb or IL-4 and anti–IFN-γ mAb. The percentages of IFN-γ– and IL-4–producing cells are shown. Representative dot plots from a control subject and a *STAT3* patient are shown on the left, and pooled data from eight control subjects and eight *STAT3* patients showing percentages of CD4+IFN-γ+ cells and CD4+IL-4+ cells are on the right. (B) Naive CD4+ T cells from eight control subjects and eight *STAT3* patients were stimulated with anti-CD3/CD28 mAbs, and the concentration of IFN-γ, IL-5, and IL-13 in the culture supernatants was measured by ELISA. Pooled data from eight control subjects and eight *STAT3* patients are shown. (C) PBMCs from eight control subjects and eight *STAT3* patients were stimulated, and the concentration of IFN-γ, IL-5, and IL-13 was measured as in B. Pooled data from eight control subjects and eight *STAT3* patients are shown. Data are representative of at least two independent experiments performed in triplicate. (A–C) Horizontal bars indicate mean values. *, $P < 0.05$.

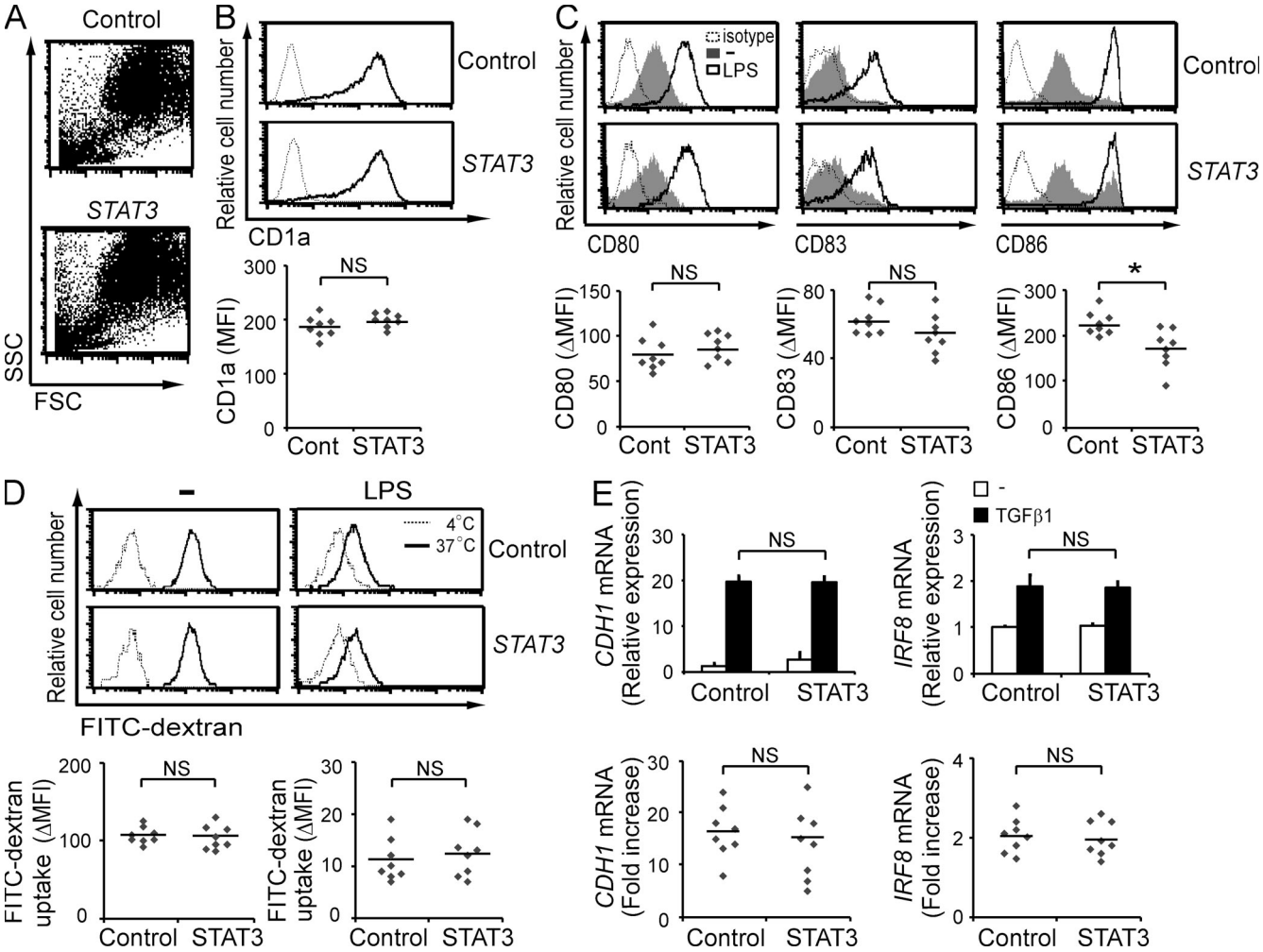


**Figure S2. MoDC differentiation in vitro and TGF-β1 signaling in MoDCs are intact in *STAT3* patients.** (A) Representative forward and side light scatter (FSC and SSC, respectively) profile of immature DCs from a control subject and a *STAT3* patient. (B) Representative histograms of CD1a expression on immature DCs are at the top, and summary data from eight control subjects and eight *STAT3* patients showing mean fluorescence intensity (MFI) of CD1a expression are at the bottom. Dashed line indicates staining with an isotype-matched control mAb. (C) Representative histograms of CD80, CD83, and CD86 expression on immature MoDCs (−) and LPS-matured MoDCs (LPS) from a control (Cont) subject and a *STAT3* patient are shown at the top, and summary data ($n$ = 8 each) showing ΔMFI, LPS stimulated minus immature, are at the bottom. Dashed lines indicate staining with isotype-matched control mAbs. (D) Representative histograms of FITC-dextran uptake by immature (−) and LPS-matured (LPS) MoDCs from a control subject and a *STAT3* patient are shown at the top, and summary data ($n$ = 8 each) showing ΔMFI, cultures in 37°C minus cultures in 4°C, are at the bottom. Data are representative of at least two independent experiments. (E) Immature DCs from a control subject and a *STAT3* patient were stimulated with TGF-β1 for 4 h, and the amount of *CDH1* (E-cadherin) and *IRF8*, TGF-β–responsive genes, was evaluated by Q-PCR. Data shown were normalized to *HPRT* levels, and the expression level in unstimulated control cells was defined as 1.0. Representative data are shown at the top, and summary data showing fold increase ($n$ = 8 each) are at the bottom. Data are representative of two independent experiments. Graphs show mean ± SD. (B–E) Horizontal bars indicate mean values. *, $P < 0.05$.

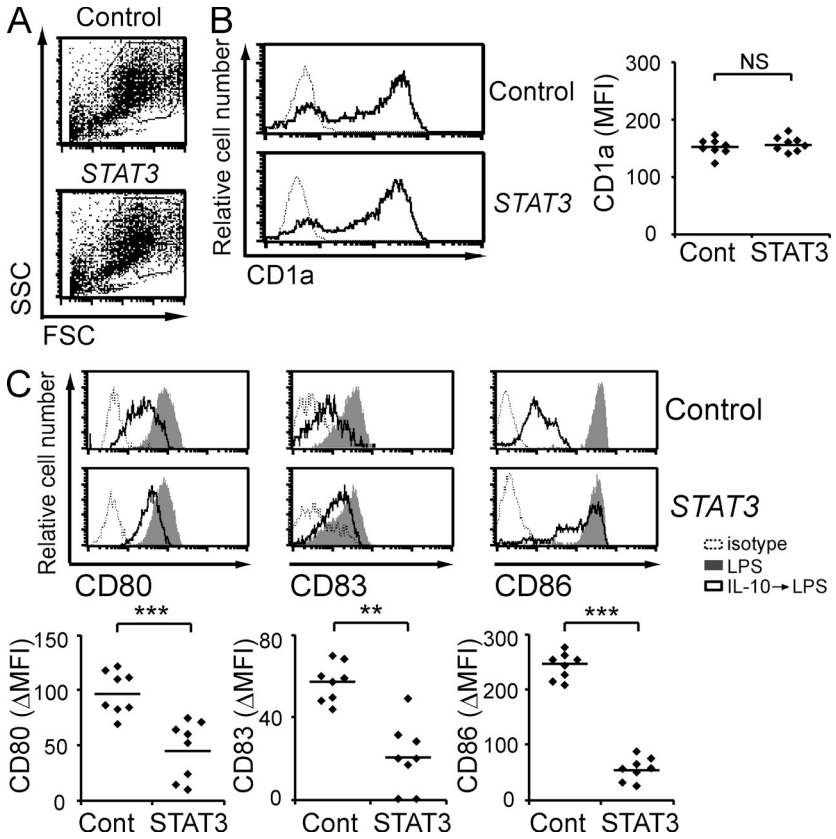


**Figure S3. IL-10 treatment does not impair the differentiation of MoDCs, but down-regulation of CD80, CD83, and CD86 is defective in MoDCs from *STAT3* patients.** (A) Representative forward and side scatter (FSC and SSC, respectively) profile of IL-10–treated MoDCs. (B) Representative histograms of CD1a expression on IL-10–DCs from a control (Cont) subject and a *STAT3* patient. Dashed lines indicate the staining with isotype-matched control mAb. Representative histograms are on the left, and summary data ($n$ = 8 each) showing mean fluorescence intensity (MFI) of CD1a expression are on the right. Data are representative of at least two independent experiments. (C) Representative histograms of CD80, CD83, and CD86 expression on LPS-matured DCs (LPS) and LPS-matured MoDCs after prior treatment with IL-10 (IL-10 → LPS) from a control subject and a *STAT3* patient. Dashed lines indicate staining with isotype-matched control mAbs. Summary data ($n$ = 8 each) showing ΔMFI, LPS matured minus IL-10 → LPS DCs, of CD80, CD83, and CD86 are on the bottom. Data are representative of at least two independent experiments. (B and C) Horizontal bars indicate mean values. **, $P < 0.01$; ***, $P < 0.001$.

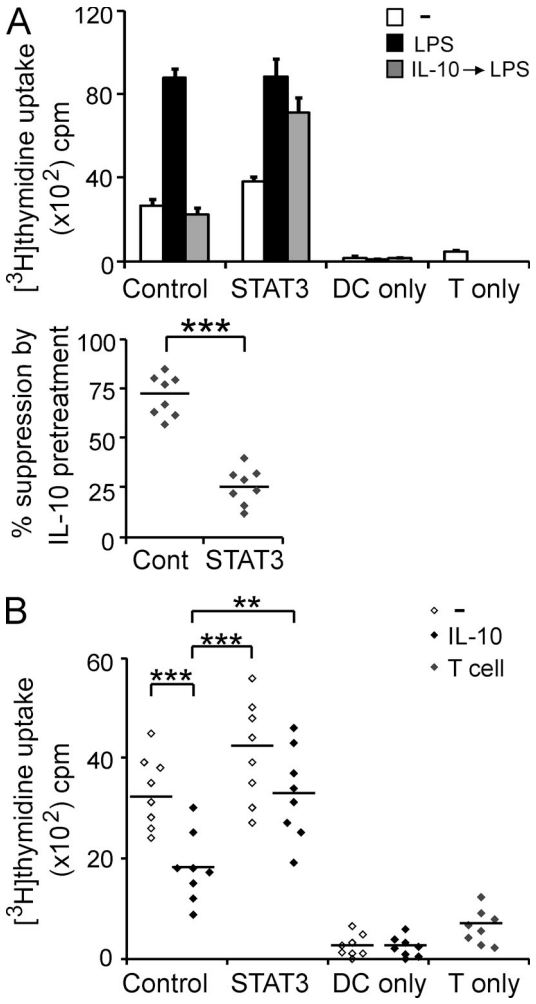


**Figure S4. Suppression of proliferation by IL-10 pretreatment is impaired in MoDCs from *STAT3* patients.** (A) Third-party allogeneic naive CD4+ T cells from control (Cont) subjects were co-cultured with immature DCs (−), LPS-matured DCs (LPS), or LPS-matured DCs after prior treatment with IL-10 (IL-10 → LPS). After 5 d, proliferation was evaluated by pulsing with 1 µCi (37 kBq) [$^3$H]thymidine for the final 18 h. Representative data from a control subject and a *STAT3* patient are shown at the top, and summary data ($n$ = 8 each) showing percent suppression are at the bottom. Graph shows mean ± SD. (B) Allogeneic third-party naive CD4+ T cells from control subjects were co-cultured with immature DCs (−) or IL-10–DCs (IL-10) from control subjects and *STAT3* patients. After 5 d, proliferation was evaluated as in A. Summary data from eight control subjects and eight *STAT3* patients are shown. Data are representative of at least two independent experiments performed in triplicate. (A and B) Horizontal bars indicate mean values. **, $P < 0.01$; ***, $P < 0.001$.

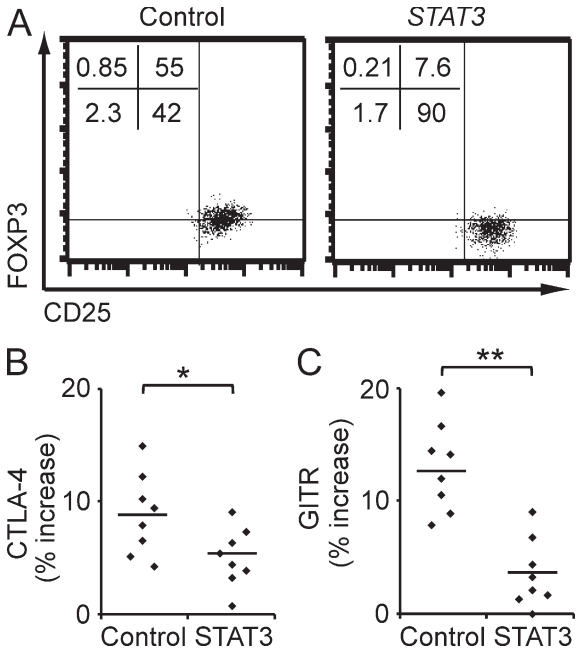


**Figure S5. Up-regulation of FOXP3, CTLA-4, and GITR is impaired in naive CD4⁺ T cells co-cultured with patient IL-10–DCs.** (A) After the co-culture of naive CD4⁺ T cells with control or patient IL-10 DCs in the presence of plate-bound anti-CD3 mAb for 5 d, CD4⁺ T cells in the small lymphoid gate were evaluated for the expression of CD25 and FOXP3. (B and C) Expression of CTLA-4 (B) and GITR (C) on CD4⁺CD25⁺ T cells cultured as in A from control subjects and *STAT3* patients was evaluated. Summary data ($n = 8$ each) showing percent increase, IL-10–DCs minus untreated DCs, are shown. Data are representative of at least two independent experiments. Horizontal bars indicate mean values. *, $P < 0.05$; **, $P < 0.01$.

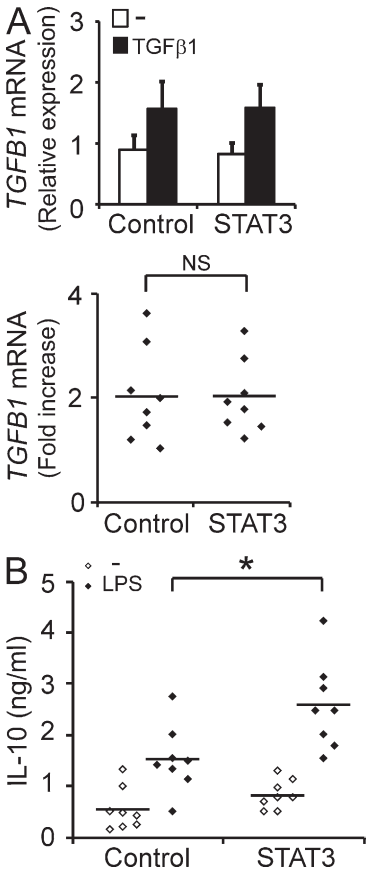


**Figure S6. MoDCs from *STAT3* patients produce equivalent amounts of TGF-β1.** (A) Immature DCs from a control subject and a *STAT3* patient were stimulated with TGF-β1 for 4 h, and the amount of *TGFB1* mRNAs was analyzed by Q-PCR. Data shown were normalized to *HPRT* levels, and the expression level in unstimulated control cells was defined as 1.0. Representative Q-PCR data are at the top, and summary data ($n$ = 8 each) showing fold increase are at the bottom. Graph shows mean ± SD. (B) Summary data of IL-10 levels of culture supernatants of unstimulated immature MoDCs (−) and LPS-stimulated MoDCs (LPS) from eight control subjects and eight *STAT3* patients. Data are representative of at least two independent experiments performed in triplicate. (A and B) Horizontal bars indicate mean values. *, $P < 0.05$.

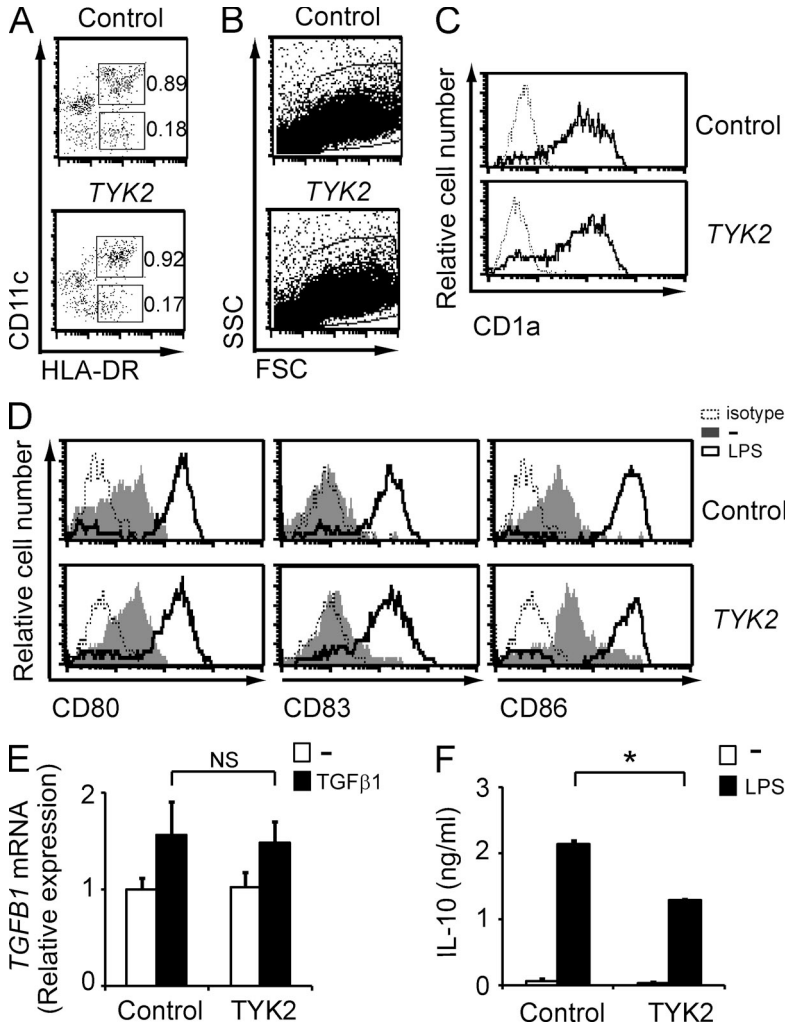


**Figure S7. Characterization of primary DCs and MoDCs of the patient with *TYK2* deficiency.** (A) Lin-negative cells in PBMCs from a control subject and the *TYK2*-deficient patient were evaluated for the expression of HLA-DR and CD11c. CD11c$^+$ cells are cDCs, and CD11c$^-$ cells are pDCs. (B) Forward and side scatter (FSC and SSC, respectively) profile of immature DCs of a control subject and the *TYK2*-deficient patient. (C) Histogram of CD1a expression on immature DCs of a control subject and the *TYK2*-deficient patient. (D) Expression levels of CD80, CD83, and CD86 on immature MoDCs (−) and LPS-matured MoDCs (LPS). (C and D) Dashed lines indicate staining with isotype-matched control mAbs. (E) Immature DCs from a control subject and the *TYK2*-deficient patient were stimulated with TGF-β1 for 4 h, and the amount of *TGFB1* mRNAs was analyzed by Q-PCR. Data shown are normalized to *HPRT* levels, and the expression level in unstimulated control cells was defined as 1.0. (F) IL-10 levels in the culture supernatants of unstimulated immature MoDCs (−) and LPS-matured MoDCs (LPS) from a control subject and the *TYK2*-deficient patient. Data are representative of at least two independent experiments. (E and F) Graphs show mean ± SD. *, $P < 0.05$.