Cutting Edge: Human Regulatory T Cells Require IL-35 To Mediate Suppression and Infectious Tolerance

Vandana Chaturvedi, Lauren W. Collison, Clifford S. Guy, Creg J. Workman and Dario A. A. Vignali

*J Immunol* 2011; 186:6661-6666; Prepublished online 16 May 2011;
doi: 10.4049/jimmunol.1100315
http://www.jimmunol.org/content/186/12/6661

Supplementary Material
http://www.jimmunol.org/content/suppl/2011/05/16/jimmunol.1100315.DC1

References
This article cites 19 articles, 7 of which you can access for free at:
http://www.jimmunol.org/content/186/12/6661.full#ref-list-1

Subscription
Information about subscribing to The Journal of Immunology is online at:
http://jimmunol.org/subscription

Permissions
Submit copyright permission requests at:
http://www.aai.org/About/Publications/JI/copyright.html

Email Alerts
Receive free email-alerts when new articles cite this article. Sign up at:
http://jimmunol.org/alerts

Errata
An erratum has been published regarding this article. Please see next page or:
/content/191/4/2018.full.pdf
Human regulatory T cells (T_{reg}) are essential for the maintenance of immune tolerance. However, the mechanisms they use to mediate suppression remain controversial. Although IL-35 has been shown to play an important role in T_{reg}-mediated suppression in mice, recent studies have questioned its relevance in human T_{reg}. In this study, we show that human T_{reg} express and require IL-35 for maximal suppressive capacity. Substantial upregulation of EBI3 and IL12A, but not IL10 and TGFB, was observed in activated human T_{reg} compared with conventional T cells (T_{conv}). Contact-independent T_{reg}-mediated suppression was IL-35 dependent and did not require IL-10 or TGF-β. Lastly, human T_{reg}-mediated suppression led to the conversion of the suppressed T_{conv} into iT_{35} cells, an IL-35–induced T_{reg} population, in an IL-35–dependent manner. Thus, IL-35 contributes to human T_{reg}-mediated suppression, and its conversion of suppressed target T_{conv} into IL-35–induced T_{reg} may contribute to infectious tolerance. The Journal of Immunology, 2011, 186: 6661–6666.

Interleukin-35 (EBI3–IL-12A/IL12A) heterodimer is required for murine regulatory T cells (T_{reg}) function (1) and has been shown to induce the conversion of murine and human conventional T cells (T_{conv}) into IL-35–induced T_{reg} (iT_{35}) (2). Furthermore, IL-35 is produced by human T_{conv} exposed to rhinovirus-infected dendritic cells (3) and human peripheral blood CD4+ T cells from chronic hepatitis B virus-infected patients (4). However, two studies have suggested that human T_{reg} neither express nor produce IL-35, increasing the controversy surrounding the physiological importance of IL-35 in human T_{reg} (5, 6). Several studies have shown that both murine and human T_{reg} can mediate infectious tolerance, the contiguous spread of suppressive capacity from T_{reg} to the suppressed target cell. The mechanisms used to mediate this induction and the subsequent mechanisms used by this induced regulatory population to mediate suppression remain obscure (7–9). However, studies with human T_{reg} have suggested that IL-10 and TGF-β may contribute to these events (10, 11). Nevertheless, mechanistic insight into the regulatory preferences of human T_{reg} is lacking.

Materials and Methods

Cell isolation, expansion, and labeling

CD4+ T cells were obtained and purified from human cord blood or apheresis rings, as previously described (2, 12). Purity was verified by intracellular staining of FOXP3 (eBioscience, San Diego, CA). T_{reg} and T_{conv} were expanded in X-VIVO medium containing beads coated with anti-CD3 and anti-CD28 (bead/cell ratio 1:1), 20% (v/v) human sera (Lonzar, Conshohocken, PA), and either 100 IU/ml human IL-2 for T_{reg} or 100 IU/ml for T_{conv} (10, 11). For CFSE or eFluor670 labeling, freshly purified naïve T_{conv} or T_{reg} were resuspended in PBS (0.1% BSA) at 2 × 10^6 cells/ml, incubated with CFSE or eFluor670 (1 μM) for 10 min at 37˚C, stopped with ice-cold PBS, and washed three times in culture media. All experiments using expanded T_{reg} were performed at least 9 d postactivation.

RNA isolation and real-time PCR analysis

Analysis was performed as previously described (1, 2). Sequences are detailed in Supplemental Table I.

Intracellular staining and immunofluorescence

Analysis was performed as previously described (1, 2). PE-conjugated anti–IL-12A (clone 27537) and IgG1 (isotype control; clone 25711) were used for immunofluorescence and intracellular staining (R&D Systems, Minneapolis, MN). The 8E fix/perm buffer used for intracellular staining of IL-12A was kindly provided by Dario Campana (St. Jude Children’s Research Hospital).

T_{reg} suppression assay

Assay was performed as previously described (2, 12). Briefly, 96-well round-bottom microtiter plates were used to perform standard suppression assays. Freshly purified 5 × 10^4 naïve T_{conv} were activated with anti-CD3/anti-CD28-coated latex beads and IL-2 (10 IU/ml) and used as target cells with varying concentrations of naïve T_{reg} in vitro-activated T_{reg} or CFSE-labeled suppressed T_{conv}. The cultures were pulsed with 1 μCi [3H]thymidine for the final 8 h of the 5-d assay and harvested with a Packard harvester (PerkinElmer). Counts per minute were determined using a Packard Matrix 96 direct counter (PerkinElmer, Waltham, MA).

Transwell experiments were performed in 96-well Transwell plates with a 0.4 μm pore size (Millipore, Billerica, MA). Freshly purified naïve T_{conv} were activated as described above and used as target cells in the bottom chamber of the 96-well plate. The suppressor populations in the top chamber of the Transwell were activated T_{reg} activated T_{reg} cultured with naïve T_{conv} or suppressed T_{conv}. In some experiments, cocultured naïve T_{conv} were fixed with 4% formaldehyde for 10 min at room temperature and washed twice prior to assay. The suppressor population was activated with anti-CD3/anti-

Department of Immunology, St. Jude Children’s Research Hospital, Memphis, TN 38105

Received for publication February 7, 2011. Accepted for publication April 25, 2011.

This work was supported by the National Institutes of Health (Grants R01 AI39480 and 38105). D.A.A.V.), and the American Lebanese Syrian Associated Charities (to D.A.A.V.).

Address correspondence and reprint request to Dr. Dario Vignali, Department of Immunology, St. Jude Children’s Research Hospital, 262 Danny Thomas Place, Memphis, TN 38105-3678. E-mail address: vignali.lab@stjude.org.

The online version of this article contains supplemental material.

Abbreviations used in this article: iT_{35}, IL-35–induced regulatory T cell; T_{conv}, conventional T cell; T_{reg}, regulatory T cell.

Copyright © 2011 by The American Association of Immunologists, Inc. 0022-1767/11/$16.00.

www.jimmunol.org/cgi/doi/10.4049/jimmunol.1100315
CD28–coated latex beads and IL-2 (40 IU/ml). Where indicated, neutralizing anti-Ebi3 (clone V1.4F5.25) (2) anti–IL-10 (JES39D7; BioLegend, San Diego, CA), anti–TGF-β (1D11; R&D Systems), or isotype controls were added. A combination of both anti-Ebi3 (clone V1.4F5.25) and anti–IL-12A (clone 27537) was used at indicated concentrations when anti–IL-35 Ab was used in neutralization studies. After 112 h, the top chambers were removed and [3H]thymidine was added to the bottom chambers for the final 8 h of the 5-d assay. Cultures were harvested with a Packard harvester (PerkinElmer), and counts per minute were determined using a Packard Matrix 96 direct counter (PerkinElmer).

Results and Discussion

Human umbilical cord blood is an ideal source of naive Tconv and naive Treg due to their lack of previous antigenic exposure and thus the ease with which they can be reliably purified based on CD4 and CD25 expression (data not shown). Naive cord blood Treg expressed low levels of mRNA encoding both the EBI3 and IL12A subunits of IL-35 compared with Tconv (data not shown). However, following activation with anti-CD3/anti-CD28–coated beads, EBI3 and IL12A were substantially upregulated in Treg (>35-fold over Tconv) (Fig. 1A). Although a similar observation was made with Treg isolated from adult PBMC, the fold upregulation was less, perhaps due to the difficulty of generating pure populations from adult cells (Supplemental Fig. 1A). EBI3 and IL12A expression was not induced or influenced by IL-2, as the inclusion of reduced concentrations with Treg or its inclusion with Tconv (100 IU/ml) had no effect (note that >100 IU/ml IL-2 induced Tconv death). Surprisingly, expression of IL10 and TGFβ mRNA in cord blood Treg was modest in comparison with EBI3 and IL12A. Expression of mRNA encoding the other IL-12 family members, IL23 (p19), IL27 (p28), and IL12B (p40), was not upregulated in Treg isolated from either cords or PBMC, inferring that IL-35 may be the only IL-12 family cytokine human Treg to have the capacity to upregulate upon activation compared with Tconv (Fig. 1A, Supplemental Fig. 1A). Expression of EBI3 and IL12A following activation remained low until day 3 postactivation, when there was a steep increase compared with similarly activated Tconv (>100-fold), which was maintained through day 9 (Fig. 1B, 1C). We note that previous studies suggesting that human Treg do not express EBI3 and IL12A only analyzed expression in resting or activated Treg up to day 2 poststimulation (10, 11).

FIGURE 1. Human Treg express IL-35. CD4+CD25− (Tconv) and CD4+CD25+ (Treg) were purified by FACS from cord blood. A, Relative mRNA expression in Treg was determined. B and C, Cell types noted were analyzed for EBI3 or IL12A expression at the indicated days postactivation. Naive Tconv were used for normalization (arbitrarily set to 1). D, At indicated time points, Tconv (blue) and Treg (red) were stained with anti–IL-12A or isotype control. A representative histogram (left panels) and the mean percentage of IL-12A high cells (right panels) are depicted. E, Activated cells were restimulated with PMA plus ionomycin for 6 h and then stained with an isotype control or anti–IL-12A (yellow) plus phalloidin (actin, gray) and DAPI (nucleus, blue). Original magnification ×63 Data represent the mean ± SEM of 4 to 5 (A), 5 (B, C, E), and 8, 13, and 11 (D) independent experiments at the three time points indicated. *p < 0.05, **p < 0.005, ***p < 0.001.
Comparable, minimal intracellular expression of IL12A (p35) was seen in resting human Treg and CD4+ and CD8+ Tconv (data not shown). However, IL-12A expression increases ~10-fold following activation of human Treg but not Tconv, as determined by flow cytometry (Fig. 1D) and immunofluorescence (Fig. 1E). Although expression was bimodal (~30%) 9 d postactivation, subsequent restimulation and analysis 3 d later resulted in ~100% expression of intracellular IL-12A and further increases in IL-12A mean fluorescence (~30-fold) and EBI3 and IL12A mRNA expression (Fig. 1D, Supplemental Fig. 2A). It is possible that this bimodal IL-12A expression is related to the activation state of the Treg. It is important to note that neither activation nor reactivation substantially altered the low-level intracellular expression of IL-12A in CD4+ and CD8+ Tconv (Fig. 1D and data not shown). The basal amount of IL-35 expression detected in Tconv could be attributed to their activation state, as it has been shown that activated human Tconv also express FOXP3, TGF-β, and IL-10 and thus may express small amounts of IL-12A and EBI3, or this could be due to some low-level background due to the staining procedure (5). The relationship between FOXP3 and IL-35 expression following Tconv and Treg activation was then assessed. Whereas all the activated Tconv and Treg populations examined expressed comparable FOXP3 IL-12A expression differed (Supplemental Fig. 1B). Restimulated Treg exhibit the highest IL-12A expression, whereas a high percentage of Treg-suppressed Tconv express IL-12A and thus may be iTreg35. Although activated Tconv express low levels of IL-12A, despite high FOXP3 expression, they are unlikely to secrete IL-35 given the absence of Ebi3 mRNA. Taken together, these data demonstrate that human Treg express IL-35 to a significantly greater extent than Tconv. Furthermore, expression of FOXP3 does not necessarily endow T cells with the ability to express IL-12A/EBI3 and secrete IL-35 (6).

We next assessed whether IL-35 secretion by human Treg contributed to their function. Naive human cord blood Treg possess minimal suppressive capacity in vitro, whereas activated Treg which exhibit high levels of EBI3 and IL12A mRNA expression, are potently suppressive (data not shown). Our initial analysis suggested that IL-35 neutralization in a conventional in vitro Treg assay had a minimal effect on their suppressive capacity, likely due to the multiple contact-dependent and contact-independent mechanisms at their disposal (data not shown) (16, 17). However, activated human Treg have also been shown to mediate potent suppression when separated from their Tconv targets by a permeable Transwell membrane, emphasizing the importance of soluble factors, such as inhibitory cytokines, in mediating suppression (10, 11). Consequently, we assessed the relative contribution of IL-35 as well as IL-10 and TGF-β, two inhibitory cytokines implicated in mediating contact-independent suppression by human Treg (10, 11). Surprisingly, neutralizing anti–IL-10 and anti–TGF-β had no effect on Treg-mediated suppression (Fig. 2A). In contrast, neutralizing anti–IL-35 completely blocked suppression. Subsequent analysis demonstrated dose-dependent inhibition of Treg-mediated suppression by neutralizing anti–IL-35 (Fig. 2B). Similar observations were also made with adult PBL-derived CD4+CD25+CD45RA+ Treg (data not shown). These data suggest that IL-35, but not IL-10 and TGF-β, is required to mediate contact-independent human Treg-mediated suppression.

Infectious tolerance is thought to play a substantial role in propagating Treg-mediated immune control, but the mechanisms used to convert suppressed Tconv into an induced regulatory population and the mechanisms by which they in turn suppress third-party Tconv remain contentious. Previous studies have suggested that human Treg mediate the conversion of cocultured Tconv into IL-10- or TGF-β-induced Treg populations (10, 11). More recently, we showed that IL-35 production by murine Treg mediates the conversion of suppressed target Tconv into an induced Treg population, termed iTreg35, that mediate suppression via IL-35, but not IL-10 or TGF-β (2, 18). However, it is not known if human Treg can generate iTreg35 cells and if they contribute to immune regulation. Thus, we first assessed whether IL-35 expression and production by human Treg can be modulated following contact with Tconv and whether the latter were induced to express IL-35. Modest increases in EBI3 and IL12A mRNA and intracellular IL-12A expression were observed in functionally suppressive, cocultured Treg compared with activated Treg (Fig. 3A, 3B). However, suppressed, cocultured Tconv substantially upregulated EBI3 and IL12A mRNA and intracellular IL-12A expression to a level indistinguishable from maximally activated human Treg (Fig. 3A, 3B). Contrary to recent studies, we saw modest expression of IL10 and TGFB mRNA in activated human Treg and no evidence for increased
expression in the functionally suppressive Treg or suppressed Tconv isolated from cocultures (Supplemental Fig. 2B).

To determine if the increased EBI3 and IL12A expression observed was driven by IL-35, IL-10, and/or TGF-β, Treg/Tconv cocultures were established in the presence of neutralizing Abs. EBI3 and IL12A mRNA expression was not significantly affected by neutralization of TGF-β or IL-10 (Fig. 3A). Conversely, in the presence of neutralizing anti–IL-35, EBI3 and IL12A expression was substantially reduced in cocultured Treg and essentially prevented in cocultured Tconv (Fig. 3A). These data suggest that IL-35 generation is induced and expression maintained by IL-35 in an autocrine (in Treg) and paracrine (in suppressed Tconv) fashion following cell contact between human Treg and Tconv.

We have previously shown that activation of human Tconv in the presence of IL-35 mediates the generation of an induced Treg population, iTr35 (2). The substantial expression of EBI3 and IL12A mRNA and intracellular IL-12A expression in suppressed Tconv, and the requirement for IL-35 to mediate this induction, infers the generation of iTr35 (2). This prompted us to investigate whether these suppressed Tconv gained regulatory activity and determine the mechanism of conversion and suppression. CFSE-labeled suppressed Tconv were purified from Treg/Tconv cocultures after 3 d and their regulatory capacity determined in a secondary, standard in vitro suppression assay. These Treg-suppressed Tconv exhibited potent, dose-dependent suppressive capacity, as previously reported (Fig. 3C). To determine the cytokines responsible for induction of this regulatory capacity, Treg/Tconv cocultures were performed in the presence or absence neutralizing anti–IL-35, TGF-β, or IL-10 prior to purification and secondary suppression assay. When suppressed Tconv were isolated from cocultures established in the presence of neutralizing IL-35, IL-10, TGF-β, or an isotype control (10 μg/ml) was determined as in C. E, Assay performed as in D except that the neutralizing mAbs were added during the secondary suppression assay. Counts per minute of activated Tconv alone, in the absence of any suppression, were 70,000–125,000. Data represent the mean ± SEM of 8–14 (A) and 3 (B–E) independent experiments. *p < 0.05, **p < 0.005, ***p < 0.001.

**FIGURE 3.** Treg-mediated induction of iTr35. A and B, Activated Treg were labeled with eFluor670 and cultured with CFSE-labeled naive Tconv at a ratio of 1:4 in the presence anti-CD3/CD28–coated beads and IL-2 (10 IU/ml) with or without neutralizing mAbs against IL-35, TGF-β, or IL-10 (10 μg/ml) for 72 h. Cells were purified by FACS on day 3 and analyzed for relative expression of EBI3 (A, upper panel) and IL12A (A, lower panel) and intracellular expression of IL-12A (B). C, Regulatory capacity of the sorted suppressed Tconv was determined using naive Tconv as targets. D, Regulatory capacity of suppressed Tconv generated in the presence of neutralizing IL-35, IL-10, TGF-β, or an isotype control (10 μg/ml) was determined as in C. E, Assay performed as in D except that the neutralizing mAbs were added during the secondary suppression assay. Counts per minute of activated Tconv alone, in the absence of any suppression, were 70,000–125,000. Data represent the mean ± SEM of 8–14 (A) and 3 (B–E) independent experiments. *p < 0.05, **p < 0.005, ***p < 0.001.
regulatory capacity of T<sub>reg</sub> is insufficient to mediate effective suppression, a scenario that might occur in vivo (Fig. 4A). However, if fresh, naive T<sub>conv</sub> were added to the top well under these conditions, substantial cell contact-independent suppression across a Transwell membrane was observed (~60%), raising the possibility that iT<sub>r35</sub> generated by the human T<sub>reg</sub> could compensate for this T<sub>reg</sub> insufficiency. Indeed, this suppression was lost when the naive T<sub>conv</sub> added to the top well were fixed (and thus could not be converted to iT<sub>r35</sub>), confirming that iT<sub>r35</sub> generated in the presence of very low numbers of human T<sub>reg</sub> can mediate contact-independent suppression (Fig. 4B). Addition of neutralizing mAbs confirmed that the suppression observed was mediated by IL-35 and not TGF-β or IL-10 (Fig. 4B, 4C). These data suggest that human T<sub>reg</sub>-generated iT<sub>r35</sub> might contribute to global suppression and mediate infectious tolerance during T<sub>reg</sub> insufficiency.

Our results demonstrate for the first time, to our knowledge, that activated cord blood- and PBMC-derived human T<sub>reg</sub> express and secrete IL-35, which contributes significantly to their suppressive capacity (19). Surprisingly, there appeared to be a minimal role of IL-10 and TGF-β. These data are in contrast with previous reports suggesting that IL-35 is not expressed by T<sub>reg</sub> isolated from PBMCs (5) and that IL-35 does not play a role in suppression mediated by FOXP3-transduced T cells (6). These discrepancies may be due to the timing of analysis, purification techniques, and/or reagents used and the populations under analysis. In addition, our data suggest that human T<sub>reg</sub>-derived IL-35 mediates the conversion of suppressed T<sub>conv</sub> into iT<sub>r35</sub> that subsequently suppress via IL-35 in a manner analogous to our observations in the mouse (2). These parallels raise the possibility that iT<sub>r35</sub> may constitute a mechanism of infectious tolerance in humans. These findings suggest that IL-35 neutralization may represent a valid immunotherapeutic strategy for the treatment of cancer and conditions in which excessive regulatory control might exist.

**Acknowledgments**

We thank Kate Vignali for technical assistance, Jessie Ni for Abs, Dario Campana for the 8B permeabilization buffer, Brandon Triplet, Michelle Howard, and Melissa McKenna at St. Louis Cord Blood Bank for cord blood samples, and the staff of the Blood Donor Centre at St. Jude Children’s Research Hospital for aphaeresis rings. We also thank Richard Cross, Greig Lennon, and Stephanie Morgan for FACS and the staff of the Hartwell Center for Biotechnology and Bioinformatics at St. Jude for real-time PCR primer/probe synthesis.

**Disclosures**

D.A.A.V., L.W.C., and C.J.W. have submitted patents that are pending and are entitled to a share in net income generated from licensing of these patent rights for commercial development.

**References**


Letter of Retraction

We wish to retract the article titled “Human Regulatory T Cells Require IL-35 To Mediate Suppression and Infectious Tolerance” by Vandana Chaturvedi, Lauren W. Collison, Clifford S. Guy, Creg J. Workman, and Dario A. A. Vignali, *The Journal of Immunology*, 2011, 186: 6661–6666.

A recent review by our research team found the approaches used by the first author, Vandana Chaturvedi, to calculate data in several suppression assays (Fig. 3C–E) to be flawed. The authors feel there is sufficient concern over these data in the article that retraction is warranted. All the authors concur with this retraction and sincerely regret any inconvenience this may have caused.

Vandana Chaturvedi
Department of Pediatrics and Infectious Diseases
Cincinnati Children’s Hospital
Cincinnati, OH

Lauren W. Collison
Opexa Therapeutics
The Woodlands, TX

Clifford S. Guy
Creg J. Workman
Dario A. A. Vignali
Department of Immunology
St. Jude Children’s Research Hospital
Memphis, TN