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Fine-Tuning of Regulatory T Cell Function: The Role of Calcium Signals and Naïve Regulatory T Cells for Regulatory T Cell Deficiency in Multiple Sclerosis

Alexander Schwarz,* Marijana Schumacher,* Daniel Pfaff,* Kai Schumacher,* Sven Jarius,* Bettina Balint,* Heinz Wiendl,† Jürgen Haas,* and Brigitte Wildemann*

The suppressor function of regulatory T cells (Tregs) is impaired in multiple sclerosis (MS), but the mechanisms underlying this deficiency are not fully understood. As Tregs counteract the sustained elevation of intracellular calcium, which is indispensable for full activation of conventional T cells (Tcons), we hypothesized that interference with this pathway might prompt MS-related Treg dysfunction. Using single-cell live imaging, we observed that Tregs rapidly reduce Ca\(^{2+}\) influx and downstream signals in Tcons upon cell contact, yet differ in their potency to efficiently suppress several target cells at the same time. Strikingly, individual Tregs harboring a CD4\(^{+}\)CD25\(^{+}\)FOXP3\(^{+}\)CD45RA\(^{-}\) naïve phenotype suppressed significantly more adjacent Tcons than did CD4\(^{+}\)CD25\(^{+}\)FOXP3\(^{+}\)CD45RA\(^{-}\) memory Tregs. Some constituents even completely failed to dampen Tcon Ca\(^{2+}\) influx and were contained exclusively in the memory subset. In accordance with their more powerful suppressive performance, the Ca\(^{2+}\) signature was considerably enhanced in naïve Tregs in response to TCR triggering, compared with the memory counterparts. MS Tregs displayed a significantly diminished suppression of mean Ca\(^{2+}\) influx in the sum of individual Tcons recorded. This reduced inhibitory activity was closely linked to decreased numbers of individual Tcons becoming suppressed by adjacent Tregs and, in turn, correlated with a marked reduction of naive subtypes and concomitant expansion of nonsuppressive memory phenotypes. Thus, the superior achievement of naïve Tregs is pivotal in maintaining Treg efficiency. As a consequence, MS Tregs become defective because they lack naïve subtypes and are disproportionately enriched in memory cells that have lost their inherent downregulatory activity. The Journal of Immunology, 2013, 190: 000–000.

D4\(^{+}\)CD25\(^{+}\)FOXP3\(^{+}\) regulatory T cells (Tregs) are key players in maintaining immunological self-tolerance, and a functional Treg deficiency is associated with various autoimmune diseases, including multiple sclerosis (MS) (1, 2). The ability of Tregs derived from patients with MS to downregulate both proliferation and cytokine secretion of activated conventional T cells (Tcons) in vitro is impaired, and this dysfunctional state is linked to a possibly thymic-dependent imbalance between naïve and more short-lived memory cells that compose the peripheral Treg population (3–5). In addition, other abnormalities in Tregs that constitute functionally heterogeneous subsets are likely to contribute to the Treg defect in MS (6). Thus, recent findings demonstrate that less suppressive Tregs capable of producing IFN-γ are significantly increased in the peripheral blood of patients with MS (7) and that certain subtypes of patient-derived memory Tregs exhibit a downscaled suppressive performance in response to distinct T cell–activating stimuli (8). Notably, the defective Treg state is ameliorated under disease-modifying treatment, indicating that pharmacological modulation of Tregs might prove to be a promising strategy for restoring immunological homeostasis in MS (7, 9, 10). Although the molecular mechanisms that confer inhibition and reconstitution have been poorly understood, insights from an elegant, recently published study have provided compelling evidence that Tregs counteract the sustained elevation of intracellular free Ca\(^{2+}\) ions in target cells and thus interfere with a fundamental requirement for almost all aspects of Tcon activation (11). In that study, cocultured cell populations were used to demonstrate rapid suppression of Tcon Ca\(^{2+}\) signaling by Tregs, followed by downregulation of the Ca\(^{2+}\)-dependent transcription factor NFAT1 and NF-kB as important downstream events. However, using this approach, the authors could not elucidate in detail how Tregs interact with individual surrounding Tcons, and it remains unknown whether cells composing the Treg subset differ in their overall or individual ability to suppress Ca\(^{2+}\) influx in target cells.

In this article, we hypothesized that a difference in the ability to downregulate Ca\(^{2+}\) influx in effector T cells might affect the suppressive performance of total Tregs and might be involved in the Treg defect that can be detected in patients with MS. We established an in-house, single-cell live imaging assay by which we could directly monitor Ca\(^{2+}\) signatures in a multitude of individual cells exhibiting either a CD4\(^{+}\)CD25\(^{+}\)FOXP3\(^{+}\) Treg or a CD4\(^{+}\)CD25\(^{-}\)FOXP3\(^{-}\) Tcon phenotype and closely monitor the contact-dependent impact of a single Treg on Ca\(^{2+}\) signaling in one or more adjacent Tcons. Because we and others have shown

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Abbreviations used in this article: CIS, clinically isolated syndrome suggestive of multiple sclerosis; HC, healthy control donor; MS, multiple sclerosis; Tcon, conventional T cell; Treg, regulatory T cell.

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previously that homeostatic changes in the Treg compartment affect total Treg function (3–5). Tregs were further separated according to surface expression of CD45RA in naive and memory Treg subtypes. We used this experimental approach to screen for differences in the mode of suppression between cells isolated from peripheral blood of healthy donors versus those obtained from MS patients. The recorded Ca\(^{2+}\) signaling components were correlated with the subordinate nuclear translocation of NFAT that propagates the Ca\(^{2+}\) signal to the nucleus to initiate gene transcription, as, for example, for IFN-γ or IL-2 (12). These readouts were complemented by assessing proliferative responses and cytokine release of TCR-triggered Tcons.

Materials and Methods

Human samples

Peripheral blood samples (40–50 ml) were obtained from 19 healthy control donors (HC; mean age: 33.6 ± 8 years; range: 21–55 y) and from 13 patients with relapsing-remitting MS (n = 9) or a clinically isolated syndrome (n = 4) according to the revised McDonald criteria (13); mean age of, 35.1 ± 11 years (range: 22–56 y); previous relapses, 1.8 ± 2.0 (range: 0–10); and disease duration range, 1–5 y. Ten patients had clinically active disease, and three patients were in clinical remission. None of the patients had been treated with corticosteroids within ± 3 mo prior to the time of blood sampling or had received immunomodulatory agents in the past. The protocol was approved by the University Hospital Heidelberg ethics committee, and all individuals gave written informed consent.

Cells

PBMCs were isolated by density-gradient centrifugation with Ficoll-Hypaque (Biochrom AG, Berlin, Germany). Tregs were isolated using a Regulatory CD4+CD25+ T Cell Kit (Invitrogen). The remaining Treg-depleted PBMCs were retained and, if required, Tcons were additionally isolated from PBMCs by using a CD4+T Cell Negative Isolation Kit (Miltenyi) followed by anti-CD28 mAbs to induce with 2.5 × 10^5 Tregs (ratio: 1:2). For calcium imaging, cells were loaded with Fura-2 AM (Invitrogen) in culture medium (RPMI 1640, supplemented with penicillin–streptomycin and 5% FCS) at room temperature in a sandwiched, self-assembled chamber. Tregs that had been prestimulated for 24 h with anti-CD3 and anti-CD28 mAbs were allowed to adhere to a poly-L-lysine–coated (0.1 mg/ml; Sigma-Aldrich) glass coverslip at room temperature in HBSS medium with Ca\(^{2+}\) and Mg\(^{2+}\), but no phenol red added.

 Live-cell imaging

In coculture assays with prestimulated Tregs, IL-2 and IFN-γ mRNA production in Tcons is considerably suppressed within hours after TCR stimulation (14). As IL-2 and IFN-γ transcription critically depends on the effective activation of the preceding Ca\(^{2+}\)/NFAT pathway, we established a live-cell imaging protocol to determine the impact of prestimulated Tregs on Ca\(^{2+}\) signaling and subordinate nuclear translocation of NFAT in Tcons. The setting of the live-cell imaging system is schematically shown in Supplemental Fig. 1.

With this setup, isolated Tregs can be reunited with PBMCs or Tcons on site. Tregs that had been prestimulated for 24 h with anti-CD3 and anti-CD28 mAbs were allowed to adhere to a poly-L-lysine–coated (0.1 mg/ml; Sigma-Aldrich) glass coverslip at room temperature in a sandwiched, self-assembled chamber, which permits solution exchanges within < 1 s. Subsequently, PBMCs or Tcons were inserted into the chamber; they descended to the bottom and occupied the interspace between Tregs, thereby forming random cell–cell contacts (Supplemental Fig. 2, Supplemental Video 1). Single-cell NFAT expression was analyzed in the cell-free supernatant by time-resolved fluorimetry (15). Cells were either immediately used or stored at 4°C for 2 weeks.

Classification of cell populations and NFAT localization

To classify the different cell populations and the subcellular distribution of NFAT, cells were immediately fixed (Fixation & Permeabilization Buffer; eBioscience) on the microscope stage after the experiment, permeabilized, and stained with fluorescent mAbs obtained from BD Pharmingen (anti–human CD3 Pacific blue, anti–human CD4 PerCP), Dako (anti–human CD25, PE), eBioscience (anti–human FOXP3-AF647), Santa Cruz Biotechnology (anti–human NFATc1-AF488), and BD Pharmingen (CD45RA APC-H7). Nuclei were stained with DAPI (Sigma-Aldrich). For epifluorescence, microscopy standard filter sets (AHF; Analysetechnik) were used (Supplemental Fig. 3).

Cytokine assays

To assess cytokine production, PBMCs or Tcons were stimulated in culture medium (RPMI 1640 medium, supplemented with penicillin–streptomycin and 5% FCS) with anti-CD3/CD28 mAbs in the live-cell imaging measurement chamber either alone or in the presence of Tregs (ratio 1:1). The supernatants were retained by exchanging the chamber solution and analyzed by ELISA (R&D Systems Europe).

Proliferation assays

In vitro proliferation assays were performed as previously described (3, 5). In brief, 10^5 freshly isolated Tcons were incubated alone or in coculture with 2.5 × 10^5 Tregs (ratio: 4:1) and polyclonally activated by adding soluble anti-CD3 (1 µg/ml) and anti-CD28 mAbs (1 µg/ml). After 4 d, cells were pulsed for 16 h with 1 µCi [3H]-thymidine per well. After harvesting, T cell proliferation was measured with a scintillation counter.

Flow cytometry

Treg and Tcon subtypes were identified and quantified using multicolor flow cytometry after surface staining of PBMCs with mAbs specific for CD3, CD25, CD127, CD45RA, and CD31 and intracellular staining for FOXP3, as previously described (3, 5).

Data analysis

For data analysis, single-cell signals were extracted from the raw data with NIS-Elements AR (Nikon). Data were processed to determine characteristic signaling patterns individually, using Igor Pro (WaveMetrics). Statistical analysis was performed with Excel (Microsoft) and IBM SPSS Statistics software, version 20.0 (SPSS, Chicago, IL). A nonparametric test (two-tailed Mann–Whitney U test) was applied for statistical analysis of Ca\(^{2+}\) data. Fisher’s exact test was used to examine the significance of categorical data. A p value <0.05 was considered significant.

Data collection was controlled by NIS-Elements 3.0 software (Nikon). Ratio images were recorded at intervals of 10 s. Single-cell Ca\(^{2+}\) signals were obtained by manually inserting regions of interest into the recorded imaging experiment. Calcium influx [Ca\(^{2+}\)] was calculated according to the relation [Ca\(^{2+}\)] = R_{max} - R_{max} - R_{max} - R_{max} - R_{max}, where the values of Kr, R_{max}, and R_{max} were determined by calibrating the setup with Fura-2 pentapotassium salt (Invitrogen) and calcium buffers (Invitrogen). Fig. 1 shows different readouts of calcium influx that were calculated for each imaging experiment: maximum peak level = [Ca\(^{2+}\)]_{max}, area under the curve = [Ca\(^{2+}\)]_{osc}, number of oscillations = [Ca\(^{2+}\)]_{osc} and cumulative duration of oscillations = [Ca\(^{2+}\)]_{cum}.

![FIGURE 1. Readouts of Ca\(^{2+}\) signaling. The recorded calcium influx of a single Tcon following TCR triggering obtained by live-cell imaging is shown schematically. auc, Area under the curve = total calcium influx; max, maximum peak level of Ca\(^{2+}\) influx; osc, number of Ca\(^{2+}\) peaks; t-osc, cumulative duration of oscillations.](http://www.jimmunol.org/)

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Results
Tregs rapidly reduce Ca\(^{2+}\) influx and downstream signals in Tcons upon cell contact

We used single-cell live imaging to analyze the influence of Tregs on cell contact–dependent Ca\(^{2+}\) signaling in Tcons (Fig. 1). Tcons derived from HC (n = 11) were TCR triggered in the presence of prestimulated syngeneic Tregs (2:1 ratio), and Ca\(^{2+}\) influx was comparatively assessed in individual Tcons with (n = 361) or without (n = 499) close contact with Tregs (as defined by overlapping CD4 surface-staining signals). We found that intimate contact with Tregs was essential to suppress Ca\(^{2+}\) signaling and Ca\(^{2+}\)-driven nuclear import of NFAT in Tcons. In contrast, calcium signaling was either not downregulated ([Ca\(^{2+}\)]\(_{\text{max}}\), [Ca\(^{2+}\)]\(_{\text{auc}}\)) or only marginally downregulated ([Ca\(^{2+}\)]\(_{\text{osc}}\), [Ca\(^{2+}\)]\(_{t-\text{osc}}\)) in Tcons that did not have direct contact with Tregs (as shown, for example, in Fig. 2; data given in Fig. 3).

Ca\(^{2+}\) signals in Tcons not having contact with Tregs did not significantly differ from Tcons that were stimulated in the absence of Tregs. We did not observe any effects on Ca\(^{2+}\) signals when Tcons were TCR triggered in the presence of non-prestimulated Tregs or if prestimulated Tcons were used instead of prestimulated Tregs (not depicted).

We next aimed to verify whether the experimental conditions were appropriate for inhibiting functional consequences of T cell activation. PBMCs were TCR stimulated alone or in the presence of HC Tregs (n = 4). Tregs efficiently suppressed IL-2 and IFN-\(\gamma\) (Fig. 3C) production by Tcons as early as 24 h after stimulation, as determined by serial assessment of suppression supernatants. Both Treg-mediated inhibition of Tcon Ca\(^{2+}\) signaling and calcium influx in Tregs upon TCR triggering are reduced in MS

To test the hypothesis that the functional Treg defect in MS is linked to an impaired interference with Ca\(^{2+}\) signaling in target...
Tcons, we used single Tcons and Tregs obtained from MS patients \((n = 9)\) and HCs \((n = 9)\) to determine whether cell contact-dependent Ca\(^{2+}\) influx was reduced in Tcons. In total, 1539 cell clusters composed of one single Treg and one to six surrounding Tcons were assessed. On average, HC-derived Tregs downregulated the maximum Ca\(^{2+}\) influx in the sum of Tcons recorded by 61.9 \pm 23.4\%. When using cells from MS patients, the mean suppression of \([\text{Ca}^{2+}]_{\text{max}}\) mediated by Tregs was clearly reduced \((38.0 \pm 15.4\%); \ p = 0.02; \text{Fig. 4A})\.

To elucidate this difference in more detail, we next determined the number of Tcons that were suppressed by a single Treg. A single Tcon was classified as “suppressed” when its maximum Ca\(^{2+}\) influx was reduced by \(\geq 15\%\) upon forming cell contact with one Treg. When using HC-derived cells, almost three fourths \((72.6 \pm 4.7\%\) of Tcons displaying close contact with the index Treg became rapidly suppressed \((\text{Fig. 4B})\), thereby demonstrating the ability of Tregs to simultaneously inhibit more than one target cell at the same time. The number of adjacent Tcons per single Treg had no impact on Treg inhibition rates and did not differ between study cohorts \((\text{HC: mean, 2.8 \pm 0.6 Tcons per Treg; MS: mean, 3.2 \pm 0.5 Tcons per Treg; } p = 0.23)\). Strikingly, MS Tregs suppressed significantly fewer surrounding Tcons, and a reduction in \([\text{Ca}^{2+}]_{\text{max}}\) could be detected only in 63.8 \pm 10.3\% Tcons \((p = 0.04; \text{Fig. 4B})\). Notably, a small contingent of Tregs completely failed to reduce \([\text{Ca}^{2+}]_{\text{max}}\) in any surrounding Tcons, and this fraction of “nonsuppressors” was significantly higher among MS Tregs \((\text{mean: 24.4 \pm 11.8\%})\) than HC Tregs \((\text{mean: 13.6 \pm 5.1\%}; \ p = 0.05; \text{Fig. 4C})\). As a contrasting observation, half of HC Tregs \((53.0 \pm 8.7\%\)\), but only 31.6 \pm 13.7\% of MS Tregs, categorically diminished \([\text{Ca}^{2+}]_{\text{max}}\) in every adjacent Tcon \((p = 0.02)\).

When percentages of “nonsuppressors” were plotted against the percentages of mean \([\text{Ca}^{2+}]_{\text{max}}\) obtained from intraindividual Tcons, we found a clear, negative correlation between overall Treg suppressive capacities and the prevalence of “nonsuppressors” \((r^2 = 0.44; \text{Fig. 4D})\).

To compare activation-induced Ca\(^{2+}\) influx in Tregs and Tcons from the two study cohorts, we separately assessed monocultures of TCR-triggered Tregs \((n = 600)\) and Tcons \((n = 800)\) \((\text{obtained from 9 MS patients, 4 CIS patients, and 13 HCs})\). We found that Ca\(^{2+}\) signals were significantly downscaled in MS Tregs, whereas the difference in Tcon Ca\(^{2+}\) signaling between study groups was not significant \((\text{Fig. 4E})\).

Parallel data from in vitro proliferation assays and live imaging of single cells obtained from the same donor were available from six patients and six HCs. As expected, HC Tregs suppressed the proliferative immune responses of Tcons much better than did MS Tregs \((\text{Fig. 4F})\).

**CD45RA\(^+\) naive Tregs exhibit superior suppressive capacities compared with memory Tregs and are reduced in MS**

We next determined inhibitory potencies of naive and memory Treg subtypes at the single-cell level. We assessed Ca\(^{2+}\) signaling patterns, together with intracellular expression of FOXP3 and surface expression of CD4, CD25, and CD45RA, in 555 individual

![FIGURE 4.](http://www.jimmunol.org/)

Both Treg-mediated inhibition of Tcon Ca\(^{2+}\) signaling and activation-induced calcium influx in Tregs are reduced in MS. Single-cell analysis of Treg-mediated suppression of \([\text{Ca}^{2+}]_{\text{max}}\) in Tcons. A total of 824 \((n = 9 \text{ MS})\) and 715 \((n = 9 \text{ HC})\) cell clusters composed of one single Treg and one to six surrounding Tcons was assessed. (A) Bars represent mean Treg-mediated suppression of \([\text{Ca}^{2+}]_{\text{max}}\) in the sum of Tcons recorded. When using cells from MS patients, the mean suppression rate was clearly reduced compared with that in HC-derived cells. \((\text{B})\) The numbers of Tcons suppressed by cell contact with Tregs are significantly reduced in MS. In the presence of patient-derived Tregs, significantly fewer Tcons show inhibition of \([\text{Ca}^{2+}]_{\text{max}}\) \((\text{HC: mean, 2.8 \pm 0.6 Tcons per Treg; MS: mean, 3.2 \pm 0.5 Tcons per Treg; } p = 0.23)\). Strikingly, MS Tregs suppressed significantly fewer surrounding Tcons, and a reduction in \([\text{Ca}^{2+}]_{\text{max}}\) could be detected only in 63.8 \pm 10.3\% Tcons \((p = 0.04; \text{Fig. 4B})\). Notably, a small contingent of Tregs completely failed to reduce \([\text{Ca}^{2+}]_{\text{max}}\) in any surrounding Tcons, and this fraction of “nonsuppressors” was significantly higher among MS Tregs \((\text{mean: 24.4 \pm 11.8\%})\) than HC Tregs \((\text{mean: 13.6 \pm 5.1\%}; \ p = 0.05; \text{Fig. 4C})\). As a contrasting observation, half of HC Tregs \((53.0 \pm 8.7\%\)\), but only 31.6 \pm 13.7\% of MS Tregs, categorically diminished \([\text{Ca}^{2+}]_{\text{max}}\) in every adjacent Tcon \((p = 0.02)\).

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**CD45RA\(^+\) naive Tregs exhibit superior suppressive capacities compared with memory Tregs and are reduced in MS**

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![FIGURE 4.](http://www.jimmunol.org/)
Tregs (obtained from five HCs and five patients). We found that CD4⁺CD25⁺FOXP3⁺CD45RA⁺ Tregs suppressed significantly more adjacent Tcons than did CD4⁺CD25⁺FOXP3⁺CD45RA⁻ memory Tregs (74.5 ± 21.1% versus 62.0 ± 25.3%; p < 0.001; Fig. 5A). Of note, nonsuppressive cells were exclusively present in the memory fraction, whereas three fourths of cells in the naive fraction showed high suppressive activity, with 50–100% suppressed Tcons (Fig. 5B). As another prominent feature, Ca²⁺ signatures recorded in TCR-triggered naive Tregs revealed considerably higher values of Ca²⁺ influx than did those in memory Tregs (Fig. 5C). Furthermore, naive Tregs exhibited lower FOXP3 expression levels than did Tregs harboring a CD45RA⁺ memory phenotype (Fig. 5D). Whether memory Tregs or naive Tregs were obtained from HC donors or MS patients had no influence on individual suppressive capacities, calcium signatures, or FOXP3 expression levels. In contrast, MS Tregs showed markedly lower numbers of CD45RA⁺ cells than did HC Tregs (HC: 37.1 ± 9.2% versus MS: 25.3 ± 11.9%; p < 0.05; Fig. 5E). This finding was confirmed by parallel flow cytometric data (available from eight patients and six HCs), revealing reduced frequencies of CD45RA⁺ naive and CD31⁺CD45RA⁺ recent thymic emigrant cells among circulating MS Tregs (naive Tregs: MS, 26.7 ± 10.4%, versus HC, 34.0 ± 6.6%, p = 0.01; recent thymic emigrant Tregs: MS, 2.6 ± 1.9%, versus HC, 4.9 ± 2.8%; p = 0.04).

Discussion

We hypothesized that interference with Ca²⁺ signaling in Tcons as a pivotal mechanism used by Tregs to confer suppression of Tcon activation might differ among Treg subsets and might contribute to the Treg defect that has been reported for MS and other autoimmune diseases (15). Our data show that normal human Tregs rapidly reduced TCR-triggered Ca²⁺ signaling and activation of NFAT in Tcons, thereby prompting the inhibition of Tcon immune activity, as reflected by substantially diminished IL-2 and IFN-γ release and dampened proliferation. These findings are well in line with the results of a recent study that used cocultured, purified T cell populations instead of single cells to demonstrate rapid suppression of Tcon Ca²⁺ signaling by Tregs, followed by downregulation of NFAT1 and NF-κB (11). The fast kinetics of cyto kinase suppression observed in our study is also consistent with the results of a previous study showing that Tregs inhibit the induction of Th1 cytokine mRNA in Tcons as early as 1 h after TCR activation (14). Calcium influx suppression was most pronounced when Tcons were in close contact with Tregs, supporting the model of contact dependency that was originally deduced from proliferation assays (16, 17) and reinforced by the more recent demonstration of gap junction formation between Tregs and Tcons (18).

Next, we comparatively assessed the impact of Tregs on Tcon Ca²⁺ signaling, using cells derived from HCs and from MS patients to elucidate in more detail how Tregs confer suppression at the single-cell level. Notably, although Tregs consistently prompted downregulation of Ca²⁺ influx in the large majority of neighboring Tcons in the HC group, the number of Tcons exhibiting a clear decrease in Ca²⁺ signals when located in direct cell contact with a single Treg was significantly decreased in MS, thus explaining the diminished performance of MS Tregs to downregulate mean calcium signals recorded from Tcons. This finding was paralleled by a marked increase in the percentage of cells among patient-derived Tregs that completely failed to suppress Ca²⁺ signaling in adjacent Tcons. These abnormalities are in line with an earlier report demonstrating that only a minority of Treg clones derived from MS patients exhibit regulatory activity (19). That and other previous studies have shown that the reduced inhibitory capacity of Tregs in MS is based on a defective performance of Treg or Treg subsets (7), and these investigations did not find evidence of an abnormal resistance of Tcons toward Treg-mediated suppressive signals (19–21). In line with this knowledge, we did not detect a higher activation state of TCR-triggered MS Tcons with respect to Ca²⁺ influx in single cells and proliferation. Thus, our data show that loss of inhibitory function in MS is not evenly distributed within the Treg population as a whole.

When we screened for distinguishing features between suppressive and nonsuppressive cells, we found that CD45RA⁺ naive cells were enriched in the fraction of Tregs classified as strongly suppressive. Consistent with the reduced proportions of strongly suppressive cells, MS-derived Tregs contained significantly fewer naive cells than did HC Tregs, which is well in line with earlier reports on disturbed T cell and Treg homeostasis in MS (3–5, 9, 10, 22, 23). Naïve Tregs featured lower FOXP3 expression, compared with Tregs from HCs, and MS Tregs were significantly enriched in the FOXP3high subset. In line with these observations, nonsuppressive cells were exclusively detected in the memory Treg subset. Thus, the activation-induced increase in Ca²⁺ influx, as revealed in this study, appears to reflect a higher reactivity of naive Tregs and suggests a more pronounced activation-dependent regulation of NFAT in Tcons, thereby prompting the inhibition of Tcon immune activity.
sustained functional fitness of this subtype. In agreement with this hypothesis, naive Tregs, unlike memory Tregs, are insensitive to apoptotic elimination, remain proliferative ex vivo, and maintain full inhibitory activity after expansion (24–26).

Taken together, our data support the idea that average, Treg-mediated suppression rates, as measured by conventional in vitro proliferation assays, directly depend on the numbers of suppressed Tcon, which in turn are determined by the prevalence of highly suppressive naive Tregs. Consequently, the homeostatic imbalance in the peripheral Treg compartment in patients with MS, as described previously (3–5), is sufficient to explain the Treg defect associated with this condition because the contraction in naive and recent thymic emigrant subtypes and the concomitant shift toward functionally exhausted memory cells containing high numbers of “nonsuppressors” obviously cannot sustain the full inhibitory capacity of total Tregs. This model also explains the physiological decline in Treg inhibitory activity in elderly persons (3). The insights gained from this study might apply to numerous other autoimmune disorders and support efforts to therapeutically strengthen the compromised activity of Tregs in human autoimmunity.

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