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Atorvastatin Induces T Cell Anergy via Phosphorylation of ERK1

Sonia Waiczies,* Timour Prozorovski,* Carmen Infante-Duarte,* Astrid Hahner,* Orhan Aktas,* Oliver Ullrich,† andFrauke Zipp2*

Modulation of T cell response is a novel property of 3-hydroxy-3-methylglutaryl (HMG)-CoA reductase inhibitors. Previously we reported the benefits of atorvastatin treatment in experimental autoimmune encephalomyelitis, the murine model of the T cell-mediated autoimmune disorder multiple sclerosis, in which a blockade of the T cell cycle by atorvastatin was attributed to an accumulation of the negative regulator p27Kip1. We show in this report that, in line with the documented role of p27Kip1 in T cell anergy, treatment with atorvastatin results in a deficient response to a second productive stimulus in human T cells. This effect of atorvastatin was dependent on HMG-CoA reduction and required IL-10 signaling. Importantly, atorvastatin induced an early and sustained phosphorylation of ERK1, but not ERK2, which was crucial for the induction of anergy. On the basis of the therapeutic impact of HMG-CoA reductase inhibitors, the present findings should pave the way for future therapeutic concepts related to tolerance induction in neuroinflammatory disorders such as multiple sclerosis. The Journal of Immunology, 2005, 174: 5630–5635.

A
torvastatin is a family member of the orally administered cholesterol-lowering agents known as statins. These drugs bind to the 3-hydroxy-3-methylglutaryl CoA (HMG-CoA)3 reductase leading to competitive displacement of the natural substrate, HMG-CoA, thereby inhibiting its catalytic conversion to l-mevalonate (1). Mevalonate is a precursor not only to cholesterol synthesis but also to intermediary lipid donors that are important for the isoprenylation of GTP-binding proteins, such as Ras, Rap1, RhoA, and RhoB (2). These small GTPases from the Ras superfamily require lipid modifications for membrane tethering and subsequent interaction with downstream effector cascades. Only then are they capable of regulating their diverse cellular functions, which include cell survival, proliferation, differentiation, and cytoskeletal organization (3). As a result of their isoprenylation requirements, GTPases are targets of statin therapy. One function of receptor-activated Ras signaling governs the accumulation of cyclin D1-cyclin-dependent kinase (CDK)4 cell cycle complexes, via the switching of MAPK signaling cascades (4). Among these cascades, the Ras/Raf/MEK/ERK signaling cascade has been demonstrated to be crucial for both T cell development and activation (5). Although it is clear that even low levels of ERK1/2 MAPK phosphorylation are sufficient to promote T cell proliferation, higher levels have been reported to promote cell cycle arrest, via the induced expression of CDK inhibitors (6, 7). We could previously show that the expression of CDK inhibitor p27Kip1 is induced by applying atorvastatin to human T cells (8). Apart from our observations in T cells, several previous reports have documented the immunomodulatory nature of statins (9–11). These studies have in fact revealed the possible benefits of using these lipid-lowering agents for the treatment of autoimmune disorders such as multiple sclerosis (MS). According to our data and those of other groups, in vivo statin treatment could prevent as well as reverse disease progression in the murine model of MS (8, 12) and in collagen-induced arthritis (13). Based on these observations, and the fact that statins are generally well-tolerated orally administered drugs, a pilot clinical study in MS (14) and a phase II trial in rheumatoid arthritis (15) have already been reported, although further clinical trials are still in progress.

We show for the first time the induction of T cell anergy by atorvastatin treatment, as a result of a HMG-CoA reductase-dependent failure of treated cells to down-regulate the anergy factor p27Kip1. Notably, we observed a robust and rapid phosphorylation of the MAPK ERK1 following atorvastatin treatment, which was independent of T cell activation. The phosphorylation of ERK by MEK1/2 was shown to be crucial for anergy induction by atorvastatin because we were able to prevent T cell hyporesponsiveness by using U0126, a specific blocker of MEK1/2.

Materials and Methods

Reagents
Pure atorvastatin (provided by Pfizer) was dissolved in 2% DMSO/ethanol (carrier was tested as vehicle control). Mevalonate was prepared, as already described, by activating l-mevalonic acid lactone (Sigma-Aldrich) (8). MEK1/2 inhibitor U0126 (Calbiochem) was used to reverse phosphorylation of ERK1/2. Human myelin basic protein (MBP) was purified, as previously described (16), and Con A was purchased from Sigma-Aldrich.

Antibodies
Anti-IL-10 (Sigma-Aldrich) was used to neutralize human IL-10. Anti-CD3/OKT3 (Orthoclone; kindly provided by Janssen-Cilag) and anti-CD28 (R&D Systems) Abs were used together for T cell stimulation. Specific primary Abs to: p27Kip1 and CDK4 (both from Santa Cruz...
Biotechnology); Ras (Oncogene Research Products); phospho-Raf, phospho-ERK1/2, ERK1/2 (all from Cell Signaling Technology); and β-actin (Sigma-Aldrich) were used for Western blot analysis.

**Peripheral immune and T cells**

PBMC (peripheral immune cells) were obtained from heparinized peripheral blood of healthy donors in accordance with local ethics committees and isolated by Ficoll Hypaque density gradient centrifugation. Immunophenotypic analysis of PBMC, on a FACSCalibur (BD Biosciences), showed that CD3⁺ T cells comprised 60.65% (range from 30 to 85%, n = 11) of PBMC. For some assays, these cells were short-term stimulated with Con A. PBMC stimulated for 4 days with TCR stimuli were termed peripheral T cells.

**Human Ag-specific T cells (T cell lines)**

Human CD4⁺ T cell lines specific for human MBP were established using a modified "split-well" protocol, as has been previously described (16). Briefly, 10⁵ PBMC were seeded in culture medium (containing 5% pooled Irradiated (3000 rad) autologous APC (10⁵) were added to each well of the master plate and to the split plate in the presence or absence of Ag. Ag specificity was tested by a standard proliferation assay. Specifically, responsive populations were selected for further expansion.

**Anergy assays**

The extent of T cell responsiveness to a second stimulus was performed as previously described (16). Briefly, resting T cell lines or PBMC (0.5 × 10⁵/ml) were stimulated with specific Ag presented by irradiated autologous APC (1.5 × 10⁵/ml) or nonspecific stimuli (2 μg/ml Con A), respectively, in 24-well culture plates for 4 days in the presence or absence of atorvastatin. Surviving T cells were thoroughly washed and restimulated with the original stimulus (in the absence of atorvastatin). The extent of T cell response to a second stimulus was determined using proliferation assays.

**[3H]Thymidine incorporation proliferation assays**

[3H]Thymidine (0.5 μCi; Amersham Biosciences) was added to each well of a proliferation assay plate. Incorporation of radioactivity was measured after 18 h with a beta counter (Microbeta; Wallac).

**Intracellular IFN-γ staining**

The flow cytometric determination of intracellular IFN-γ was performed as previously described (16). Briefly, PBMC were stimulated with 0.1 μg/ml phorbol 12-myristate 13-acetate (PMA) and 1 μg/ml ionomycin in the presence of 10 μg/ml brefeldin A. After 6 h, cells were permeabilized and stained with anti-FITC-CD4 and anti-PE-CD8 conjugated rat anti-human IFN-γ or equivalent concentration of allophycocyanin-labeled rat IgG1 isotype control Abs diluted in 0.1% saponin permeabilization solution. Analysis was performed with a FACSCalibur (BD Biosciences).

**RT-PCR and real-time quantitative PCR**

Specific primer sets were designed using Primer Express software (Applied Biosystems). ERK1 (98 bp) forward 5'-TCA TCG GCA TCG ACA A-3'; reverse 5'-GTA TGG TAC AGA CTT CCA T-3'; ERK2 (90 bp) forward 5'-CGT GAC CAC TAA AAG CCT A-3'; reverse 5'-CTG TCA GGA ACC CTG TGT C-3'; IL10 (115 bp) forward 5'-GCA GGT GAA TGC TTA TAA G-3'; reverse 5'-TCA TGG AGG CTT AGT AGT TGA A-3'; GAPDH (76 bp) forward 5'-CTC AAC TAC ATG GTC TAC ATG TCA A-3'; reverse 5'-CCA TTC TCG GGC TGT ACT GT-3'. RNA was extracted from lysed cells using the RNeasy mini kit (Qiagen). First-strand cDNA was prepared using Applied Biosystems Superscript reverse transcription reagents (Applied Biosystems). PCR (performed on a Mastercycler gradient) had the following temperature cycling profile: one cycle at 95°C for 2 min; 32 cycles at 95°C for 15 s, at 60°C (65°C for ERK1) for 1 min, and at 72°C for 30 s; one cycle at 72°C for 8 min. The PCR products were analyzed in 2% agarose gels stained with ethidium bromide. None of the primer sets resulted in detectable unspecific products when amplified from cDNA. Quantitative real-time PCR was performed on ABI Prism 7000 Sequence Detection System (PerkinElmer). Primers and probes for 18 S RNA were purchased from PerkinElmer. 18 S rRNA expressed at a constant level across all of the samples analyzed (data not shown) was selected as an internal standard. Primers and probes were designed to be introm spanning, using Primer Express software (Applied Biosystems). TGFβ CAG CTA AGG TAA AAA TGT-3', reverse 5'-TGA GGT ACG ATC GCC AGG AAT TGT-3'; probe 5'-FAM CAC GTG GTG CAC TAT AGC TAA TAC AGC TAMRA-3'; IL10 forward 5'-CAA GTT GTC CAG CAG ATC CCT CAT-3'; reverse 5'-GGC AAC CTG CCT AAC ATG CTT-3'; probe 5'-FAM AAA GAA AGT CCT CAC TCT GCT GAA GGC ATC TCG TAMRA-3'. The optimized concentrations of the primers and probes were used to detect expression levels of each variant. The following thermal cycling conditions were used: 2 min at 50°C and 10 min at 95°C followed by 40 cycles of 95°C for 1 s and 60°C for 1 min. The PCR was conducted in 25 μl of final volume. All samples were run in duplicate.

**Western blot analysis**

Immunoblot studies were performed according to standard procedures (16). Cell pellets (minimum of 3 × 10⁶ cells) were OD of the specific signal (0.15 M NaCl, 0.01 M Tris-HCl, 0.005 M EDTA, 1% Triton X-100, 2 μg/ml aprotinin, 100 μg/ml PMSF) with a Hamilton syringe. After 15 min incubation on ice, lysates were centrifuged for 15 min at 16,000 × g. Cellular lysates equivalent to 10 μg of protein, as determined by the bicinchoninic acid method (Pierce), were separated using 12% PAGE and blotted onto nitrocellulose membranes. Following 1 h blocking (5% milk powder, 2% BSA, 0.1% Tween 20) at room temperature, membranes were incubated overnight at 4°C with specific primary Abs to p27kip1, CDK4, Ras, phospho-Raf, phospho-MEK1/2, phospho-ERK1/2, ERK1/2, and β-actin. Abs were diluted in blocking buffer. Following a series of washing steps, the membranes were incubated for 1 h with 1.25 μg/ml secondary Ab coupled to HRP (Dako). Specific bands were detected using the ECL-Plus system (Amersham Biosciences). Immunoblots were sequentially probed with β-actin. The density of the band was measured with BioDocII (Biometra) documentation system, adjusted in relation to the expression of actin, and expressed as arbitrary OD index.

**Data analysis**

The individual potencies (measured in micrometers) of atorvastatin for inhibiting proliferation (IC₅₀) in Ag-specific T cell lines were determined by plotting mean percentage proliferation response as a function of increasing concentrations of the drug. The mean T cell response was calculated as an index of stimulation (SI) following Ag: cpmAg/cpmNoAg, whereas the observed percentage response was calculated as follows: (SIAg_atorva/SIag) × 100%, where Ag is Ag without drug exposure; c, control in the absence of Ag and drug; and ag_atorva, Ag incubation in presence of drug. The concentration-response profiles were fitted to a three-parameter sigmoidal Hill model, y = [a + c]/b, using SigmaPlot 2001 for Windows. The concentration of 50% (EC₅₀) was determined using SigmaPlot 2001 for Windows. The goodness-of-fit was assessed by program convergence, r² values, predicted vs observed residuals, sum of squares, and visual inspection.

**Results**

**Atorvastatin induces T cell anergy**

The dosage of atorvastatin required to produce IC₅₀ on proliferation was 3 μM for both human MBP-specific T cell stimulated with specific Ag (Fig. 1a) and freshly isolated peripheral T cells stimulated with anti-CD3/anti-CD28 (data not shown). We also observed a concomitant decrease in IFN-γ production following atorvastatin incubation in freshly isolated PBMC (Fig. 1b). Similar to our previous findings in Ag-specific T cells (8), doses higher than IC₅₀ interfered with the cell cycle of freshly isolated T cells following TCR stimulation in the presence of costimulation by inhibiting CDK4 induction and p27kip1 degradation. Expression of these cell cycle regulators was semiquantitatively analyzed and OD values, normalized against β-actin expression, are shown in Fig. 1c. The lack of degradation of the negative cell cycle regulator p27kip1 by atorvastatin (Fig. 1c) is suggestive of an induction of T cell anergy (17). In fact, apart from losing their ability to enter the cell cycle and proliferate, both Ag-specific T cell lines (Fig. 1d) and peripheral T cells (Fig. 1e) became hyporesponsive to a second stimulus following 4 days pretreatment with atorvastatin. Inhibition of IFN-γ production and induction of T cell anergy was dependent on HMG-CoA reduction because it was prevented (both
peripheral T cells and Ag-specific T cell lines) when cells were additionally pretreated with the product of HMG-CoA reduction, mevalonate (Fig. 1, b–e).

IL-10 is necessary for anergy induction by atorvastatin

As tolerance induction and impaired degradation of p27Kip1 can be induced by inhibitory cytokines such as IL-10 and TGF-β in CD4+ T cells (18, 19), we addressed whether atorvastatin-induced T cell anergy requires IL-10 production. Indeed, using both conventional PCR (Fig. 2a) and TaqMan RT-PCR (Fig. 2b), we found that atorvastatin promotes an induction of IL10 gene expression, which mevalonate strongly suppresses, suggesting an HMG-CoA reductase-dependent regulation of IL-10. In parallel we also observed by real-time PCR a similar modulation of TGFβ gene expression, although to a lesser extent, following 4 h atorvastatin treatment with Con A under varying conditions: medium (●), 10–25 μM atorvastatin (shaded bars) and in the presence (▲) or absence (■) of 200 μM mevalonate. Following 4 days atorvastatin incubation, surviving T cells were restimulated with Con A and the extent of T cell response (in the absence of both atorvastatin and mevalonate) calculated as SI (± SE) from [3H]thymidine measurements.

Rapid and strong phosphorylation of ERK1 by atorvastatin

Because atorvastatin-induced anergy in T cells was dependent on the HMG-CoA pathway, we hypothesized alterations in Ras GTP-binding protein, known to be posttranslationally modified by isoprenylation, and the protein effector pathways to be driving forces of the cell cycle machinery responsible for the observed effects of statins. We therefore analyzed the influence of atorvastatin on effector molecules of Ras, specifically the ERK group of MAPKs. Although essential for T cell survival (5), activation of ERK is also essential for specifically inducing IL-10 production (20). We preincubated T cells with 25 μM atorvastatin for 4–48 h (to differentiate short-term from long-term effects) before a brief incubation with ionomycin and PMA (for direct stimulation of the Ras signal pathway). We encountered a surprisingly strong and early phosphorylation of ERK1 but not of ERK2 in the presence of atorvastatin, in both peripheral immune cells (Fig. 3a) as well as in Ag-specific T cells (data not shown). Atorvastatin-induced ERK1 phosphorylation was abrogated when applied in the presence of a neutralizing Ab against IL-10 (Fig. 2c).
phosphorylation was several times stronger than after induction by PMA (Fig. 3a). The robust ERK1 phosphorylation (following 4 and 24 h atorvastatin treatment) prompted us to look at the kinetics of this phosphorylation, in the absence of T cell activation (Fig. 3b). Within 15 min, atorvastatin treatment resulted in the phosphorylation of ERK1, which persisted for at least 24 h. This result is in contrast to PMA-induced Ras-mediated activation of ERK1/2, which as already described in the literature, is only transiently up-regulated (data not shown). A semiquantitative analysis of which as already described in the literature, is only transiently up-regulated (data not shown). A semiquantitative analysis of

Induction of T cell anergy by atorvastatin is mediated via early ERK1 phosphorylation

Because a sustained activation of the Raf/MEK/ERK pathway was previously reported in the context of anergy induction (23), we wanted to know whether the T cell anergy induced by atorvastatin is dependent on the observed rapid and strong ERK1 phosphorylation. For this we used the MEK1/2 blocker U0126, a specific inhibitor of ERK phosphorylation, at the same concentration used in the phosphorylation experiments. In line with reports documenting the negative effects of blocking ERK1 activation on T cell development and survival (24), U0126 inhibited proliferation during the priming stimulus (Fig. 4a). However on restimulating surviving cells we were indeed able to prevent anergy induction by atorvastatin when additionally pretreating with the specific inhibitor of ERK phosphorylation (Fig. 4b).

Discussion

Induction of T cell tolerance by immunomodulatory agents is becoming an increasingly important approach for the treatment of inflammatory autoimmune disease such as MS. Anergy constitutes one means of imposing tolerance by rendering autoreactive cells functionally inactive. In the present study we report an induction of T cell anergy following in vitro application of atorvastatin, which was accompanied by an induction of IL10 as well as an accumulation of the anergy factor p27Kip1. These in vitro findings shed light onto the beneficial outcome of applying HMG-CoA reductase inhibitors such as atorvastatin for the treatment of the T cell-mediated autoimmune disorders MS (14) and rheumatoid arthritis (15). The negative cell cycle regulator p27Kip1 plays a central role in blockade of clonal expansion and is a critical downstream target of anergy induced by blockade of costimulatory pathways (17). Clonal anergy may also be induced by IL-10 and TGF-β. Application of these inhibitory cytokines results in an accumulation of p27Kip1 in alloreactive murine CD4+ T cells and renders these cells tolerant for in vivo transfer in histoincompatible recipients (18, 19). In the present study we show that atorvastatin predominately promotes IL10 gene expression in peripheral immune cells and could prevent the atorvastatin-mediated anergic condition in T cells by blocking IL-10 signaling with neutralizing Abs. These findings, together with reports documenting an induction of in vivo tolerance following exogenous application of this inhibitory cytokine (18, 19), indicate that IL-10 plays a key role in the induction of anergy by atorvastatin and could be responsible for the accumulation of p27Kip1 (18).

So far, most of the properties of statins, in particular those describing their immunomodulatory nature (8, 10), were shown to be dependent on the HMG-CoA pathway. The underlying mechanisms of most of these functions have been interpreted to be an inhibition of Ras GTP-binding protein isoprenylation (2). In the present study we also observed a dependency of anergy on the HMG-CoA pathway and anticipated Ras GTP-binding proteins and their effector molecules, upstream of the cell cycle machinery, to be negatively regulated by atorvastatin. Hillyard et al. (25) have

FIGURE 2. Induction of T cell anergy by atorvastatin necessitates IL-10 signaling. a, PBMC were activated with Con A in the presence or absence of atorvastatin with or without mevalonate (200 µM) for various periods of time. IL10 gene expression was analyzed by RT-PCR. b, PBMC were activated with Con A for 4 h in the presence or absence of atorvastatin with or without mevalonate. IL10 gene expression was analyzed by real-time RT-PCR and normalized against 18S gene expression. c, Peripheral immune cells stimulated with Con A were cultured in medium (■) or with atorvastatin (shaded bars). Some cells pretreated for 4 days with atorvastatin were also pretreated with titrating doses (500–5000 ng/ml) of neutralizing anti-IL-10 Ab (light gray bars) or 200 µM mevalonate (dark gray bar). Mean T cell response to a second Con A stimulus was calculated for each condition as SI (±SE) following Ag.

To determine whether the strong phosphorylation of ERK1 is directly mediated by the MAPK MEK1/2, we applied a selective inhibitor of MEK1/2 (U0126). Doses of U0126 specific for MEK inhibition (10 µM) (22) could delay phosphorylation of ERK1 (Fig. 3c). Atorvastatin treatment also resulted in an induction of ERK1 but not ERK2 gene expression, already within the first 4 h of treatment (Fig. 3d). Gene expression of ERK1 was normalized against GAPDH expression (Fig. 3d). Altogether these data indicate a highly specific effect of atorvastatin on ERK1 gene expression and protein phosphorylation independent of the influence on Ras.

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recently reported that a 48-h preincubation with fluvastatin inhibited FcγR-mediated activation of ERK1/2 in the monocytic cell line U937. In this study we, however, found a rapid and sustained phosphorylation of ERK1 in human T cells upon atorvastatin treatment; the level of phosphorylation was much higher than the normal threshold achieved by PMA. The anergic state of T cells treated with atorvastatin was clearly dependent on the early ERK1 phosphorylation as a consequence of Ras/Raf/MEK cascade activation, because we could prevent anergy by blocking MEK activity; the level of phosphorylation was much higher than the normal threshold achieved by PMA. In line with this, activation of ERK was previously shown to dramatically induce tyrosine phosphorylation of TCR-associated proteins and phosphorylated ERK1/2 in the cytosol (26). Although these studies are in line with the present findings, we show a highly specific effect of atorvastatin on ERK1 because we found a dramatic and sustained phosphorylation of ERK1 but not ERK2 as well as an induction of ERK1 but not ERK2 gene expression. The up-regulation of ERK1 gene expression following ERK1 phosphorylation is in line with a positive feedback loop following ERK activation proposed by Hernandez et al. (27). Also, the promoter of the ERK1 gene, unlike that of the ERK2 gene, contains no CCAAT box (28), which is important for transcription factor NF-Y/CBF binding (29). Thus it is not surprising that these two genes can be differentially regulated.

For the first time we report that atorvastatin, an immunomodulator currently under clinical investigation for the treatment of autoimmune disorders, induces anergy in human T cells as a consequence of increased IL10 expression and rapid and sustained ERK1 phosphorylation. Because survival of T cells necessitates “normal” levels of ERK1 phosphorylation, different kinetics or intensities in ERK1 signaling may determine whether autoreactive cells become tolerant or promote autoimmune processes. The cholesterol-lowering HMG-CoA reductase inhibitor atorvastatin tips over this equilibrium by inducing ERK1 phosphorylation to the extent that regulatory elements such as IL-10 and p27Kip1 may be switched on to precipitate T cell anergy.

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**FIGURE 3.** ERK1 phosphorylation following atorvastatin. a, PBMC were preincubated with atorvastatin in the presence or absence of U0126 and treated for 30 min with (+) or without (−) 100 ng/ml PMA and 1 μg/ml ionomycin (PMA/iono). Western blots were incubated with phosphorylated ERK1/2 (detects both p-ERK1 and p-ERK2), ERK1/2, and β-actin Abs. To compare the robust effect of atorvastatin on ERK1 phosphorylation (p-ERK1) with the PMA-mediated phospho-ERK1/phospho-ERK2, different film exposures to blot are indicated (5 s was enough to detect phospho-ERK1 but not phospho-ERK2 by atorvastatin and 30 s were required to detect phospho-ERK1 and phospho-ERK2 by PMA or ionomycin). b, MBP-specific T cell line MA14 was incubated with atorvastatin for the indicated periods of time. Western blot analysis reveals the kinetics of ERK1 phosphorylation and Ras accumulation by atorvastatin (without T cell activation). c, PBMC were preincubated with or without atorvastatin (25 μM) or vehicle (for atorvastatin and U0126) in the presence or absence of 10 μM U0126. d, Cells were activated with Con A in the presence or absence of atorvastatin for various periods of time; after which RNA was isolated, transcribed to cDNA and expression of ERK1 and ERK2 analyzed by PCR. Values given below p-ERK1 (a and b) and ERK1 (d) bands are OD measurements normalized against β-actin and GAPDH expression, respectively.

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**FIGURE 4.** ERK1 phosphorylation by atorvastatin is important for anergy induction. a, Priming stimulus of PBMC stimulated with 2 μg/ml Con A for 4 days in the indicated conditions: 25 μM atorvastatin (atorva), 200 μM mevalonate (mev), and 10 μM U0126. The carrier used to solubilize U0126 or atorvastatin was used as vehicle. Extent of proliferation was measured by [3H]thymidine assays as cpm (± SE). b, Peripheral immune cells stimulated with Con A were cultured with (shaded bars) or without ([]) atorvastatin and with or without U0126, mevalonate or vehicle incubation. Surviving peripheral T cells were restimulated with Con A (in the absence of atorvastatin), and the mean response to a second Con A stimulus was calculated as SI (± SE).
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Disclosures
The authors have no financial conflict of interest.

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