Inhibition of mTOR blocks the anti-inflammatory effects of glucocorticoids in myeloid immune cells

Thomas Weichhart,1 Michael Haidinger,1 Karl Katholnig,1 Chantal Kopecky,1 Marko Poglitsch,1 Caroline Lassnig,2 Margit Rosner,3 Gerhard J. Zlabinger,4 Markus Hengstschläger,3 Mathias Müller,2 Walter H. Hörl,1 and Marcus D. Säemann1

1Department of Internal Medicine III, Division of Nephrology & Dialysis, Medical University Vienna, Vienna, Austria; 2Biomodels Austria VUW and Institute of Animal Breeding and Genetics, Veterinary University of Vienna, Vienna, Austria; 3Institute of Medical Genetics, Medical University of Vienna, Vienna, Austria; and 4Institute of Immunology, Medical University of Vienna, Vienna, Austria

Introduction

Current immunosuppressive regimens to avoid allogeneic rejection after organ or bone marrow transplantation largely rely on drugs with potent immunosuppressive effects predominantly affecting different steps during T-cell activation. There is, however, increasing evidence that also the innate immune system is critical for the fate of allotransplants and may as well exert detrimental effector functions.1-9 For example, monocytes are the first cells to enter the allograft immediately after transplantation; and recently, monocyte influx, rather than T-cell influx, into the allograft has been proposed to correlate with graft rejection.9 Monocytes, macrophages, and dendritic cells (DCs) initiate the inflammatory response after stimulation by Toll-like receptor (TLR) ligands and trigger the subsequent adaptive T-cell response.10,11 However, the molecular pathways targeted by immunosuppressants in particular when they are used as combination therapy and the ensuing functional consequences are still incompletely defined.

Among the currently used immunosuppressants calcineurin inhibitors (CNI), such as cyclosporine A (CsA) or FK506, and antimetabolites, such as mycophenolic acid (mycophenolate mofetil [MMF]) are thought to exert distinct but rather modest effects on innate immune cells.12,13 On the contrary, glucocorticoids (GCs) have a high anti-inflammatory potential and, consequently, are crucial constituents of various immunosuppressive regimens applied in many inflammatory conditions.14 GCs differentially affect cytokine production in monocytes/macrophages with a prominent shift toward an anti-inflammatory phenotype.15 Furthermore, DC differentiation and maturation are profoundly suppressed by GCs, leading to DCs with a tolerizing capacity characterized by increased interleukin-10 (IL-10), but blocked IL-12 secretion.16,17 At the molecular level, GCs profoundly inhibit nuclear factor-κB (NF-κB) signaling via the glucocorticoid receptor (GR) to prevent recruitment of active NF-κB dimers to the κB promoter.18 Moreover, it has been demonstrated that the c-Jun N-terminal kinase (JNK) pathway that specifically leads to the activation of the transcription factor subunit c-Jun is blocked by transrepression through nuclear GR binding.19 Thus, NF-κB and JNK are major targets of GC to exert their anti-inflammatory action. Interestingly, NF-κB and JNK are important for the allogeneic immune response as their hyperactivation may ultimately lead to allograft rejection in diverse experimental models.20-24

The mammalian target of rapamycin (mTOR) pathway, which is known to control metabolism, growth, and cell survival, has recently emerged as key regulator of innate immune cell homeostasis.25,26 Inhibition of mTOR by rapamycin in human monocytes or myeloid DCs promotes IL-12, IL-23, tumor necrosis factor-α (TNF-α), and IL-6 production via the transcription factor NF-κB but blocks the release of IL-10 via Stat3.27,28 Conversely, deletion of TSC2, the key negative regulator of mTOR, diminishes NF-κB but enhances Stat3 activity and reverses the proinflammatory cytokine shift.27 Rapamycin can augment inflammation and pulmonary injury by enhancing NF-κB activity in the lung of tobacco-exposed mice.29 Interestingly, various inflammatory disorders have been observed in rapamycin-treated patients, such as interstitial pneumonitis, anemia of the chronic inflammatory type, and severe
forms of glomerulonephritis, despite the concomitant use of GCs. Clinical observations suggest that rapamycin-induced pulmonary pneumonitis cannot be ameliorated by high-dose glucocorticoid therapy. Moreover, kidney transplant patients on rapamycin display enhanced expression of NF-κB-related proinflammatory expression pathways and monocyte enrichment compared with CsA patients after being on steroid therapy.

In the present study, we determined the role of mTOR in monocytes and myeloid DCs in the context of other currently used immunosuppressive drugs. Our data demonstrate a conspicuous repressive role of mTOR in innate immune cells that interferes with the potent anti-inflammatory effects of GCs.

**Methods**

**Cell isolation and culture**

Peripheral blood mononuclear cells (PBMCs) were prepared from buffy coats by density gradient centrifugation using Ficoll-Paque Plus (GE Healthcare). Peripheral blood CD14+ monocytes were isolated from PBMCs by positive selection using CD14 (Miltenyi) microbeads and a magnetic cell separator. Myeloid DCs were isolated as described. THP-1, a promonocytic cell line derived from human acute lymphocytic leukemia patient, was obtained from the DSMZ. Tsc2+/−/p53−/− and Tsc2−/−/p53−/− mouse embryonic fibroblasts were a kind gift of David Kwiatkowski. Cells were cultured in RPMI 1640 (Invitrogen) containing penicillin (100 U/mL), streptomycin (100 μg/mL), glutamine (2mM), and 10% fetal calf serum that had been inactivated at 56°C for 30 minutes. Mouse embryonic fibroblasts were cultured in Dulbecco modified Eagle medium containing 4.5 g/L glucose, 2mM l-glutamine, 100 μg/mL streptomycin, 100 U/mL penicillin, and 10% fetal calf serum.

**Reagents**

Lipopolysaccharide (LPS) from *Escherichia coli* 0111:B4 was purchased from Sigma-Aldrich. Dexamethasone, MMF, CsA, and FK506 were purchased from Calbiochem. Rapamycin was used from Calbiochem or was provided by Wyeth Pharmaceuticals with identical results. Torin1 was a kind gift of Nathanael Gray.
Cell stimulation and collection of supernatants

PBMCs (1 x 10^6 cells/mL), monocytes (1 x 10^6 cells/mL), or THP-1 cells (0.5 x 10^6 cells/mL) were incubated in 24-well culture plates (Falcon; BD Biosciences) with CsA (250, 125, or 62.5 ng/mL), MMF (2.5, 0.5, or 0.1 ng/mL), or dexamethasone (250, 25, or 2.5 nM) for 1 hour at 37°C at 5% CO2 and 95% humidity before 100nM rapamycin was added. Cells were left untreated or stimulated with LPS (100 ng/mL) for 24 hours. Cell-free supernatants were harvested, stored at -20°C, and thawed at the time of analysis for IL-12p40, IL-10, and TNF-α production via Luminex.

Whole-blood stimulation

Heparinized blood from immunosuppressed renal transplant patients was diluted 1:5 in medium; 1 mL was added into 24-well plates and directly stimulated with 1 μg/mL LPS for 20 hours. Cytokines were determined in cell-free supernatants by Luminex. The study was approved by the ethics committee of the General Hospital Vienna according to the declaration of Helsinki (EK 407/2007). Informed consent was obtained from each patient.

Luminex

Cytokines were measured by Luminex Technology to IL-12p40, IL-10, IL-6, TNF-α, and MCP-1 (all R&D Systems) and IL-23 (Bender MedSystems).

RNAi

THP-1 cells were transfected in full medium without antibiotics with 100nM ON-TARGETplus SMARTpool human TSC2 or 100nM ON-TARGETplus siCONTROL nontargeting pool (Dharmacon RNAi Technologies) using Lipofectamine RNAiMAX (Invitrogen) following the protocol provided by the manufacturers. Cells were used after 72 hours.

Analysis of signal transduction events

Monocytes or THP-1 were stimulated as indicated. Extract preparation and Western blotting were done as described. Antibodies were p70S6K, p-4E-BP1 (Thr37/46), p-p38 (Thr180/Tyr182), p-S6 (Ser 240/244), S6, GAPDH (all Cell Signaling Technology), and TSC2, p-4E-BP1, p-ERK (Tyr204), ERK, and p38 (Santa Cruz Biotechnology).

Cell fractionation

Nuclear and cytoplasmic fractions were obtained by discontinuous density gradient centrifugation. Briefly, cells were applied onto a preformed iodixanol gradient and centrifuged in the cold at 10000 g for 1 hour. Subsequently, the different layers containing either cytosolic proteins or nuclear proteins were collected, and the protein concentration was determined.

T-cell proliferation

T lymphocytes were cultured at 1 x 10^6 cells/mL in 96-well flat-bottom microplates (Corning Life Sciences). T cells were stimulated with 10 μg/mL OKT-3, cultured for 2 and 3 days in the presence or absence of 25nM dexamethasone and/or 100nM rapamycin as indicated, and pulsed with [3H]TdR (1 μCi/well) for 20 hours of the culture. Assays were performed in triplicate.

T-cell differentiation

Monocytes were incubated with medium, 100nM rapamycin, and/or 25nM dexamethasone for 90 minutes and then stimulated with 100 ng/mL LPS for 24 hours. Then the cells were washed and incubated with allogeneic PBMCs at a ratio of 1:1 for one week. Afterward, IFN-γ was determined in the supernatants by enzyme-linked immunosorbent assay. In parallel, the cells were primed with 50 ng/mL phorbol myristate acetate and 200 ng/mL ionomycin for 5 hours in the presence of 10 μg/mL brefeldin A for the final 3 hours of culture. Cells were fixed and permeabilized with Fix & Perm (An der Grub) according to the manufacturer’s instructions. Cells were incubated with fluorescein isothiocyanate–labeled anti–IFN-γ, PE-labeled anti–IL-4, and allophycocyanin-labeled anti–CD4 (all BD Bioscience); then cells were washed and analyzed on a FACSCanto II.

**Table 1. Baseline characteristics of the analyzed kidney transplant patients**

<table>
<thead>
<tr>
<th></th>
<th>CsA (n = 21)</th>
<th>FK506 (n = 28)</th>
<th>Rap (n = 19)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex, % women</td>
<td>32</td>
<td>23</td>
<td>28</td>
<td>NS</td>
</tr>
<tr>
<td>Age, y</td>
<td>54.4 (13.3)</td>
<td>47.3 (17.9)</td>
<td>53.3 (16.0)</td>
<td>NS</td>
</tr>
<tr>
<td>Trough levels, ng/mL</td>
<td>95.0 (46.9)</td>
<td>9.0 (4.3)</td>
<td>7.4 (2.6)</td>
<td>NS</td>
</tr>
<tr>
<td>Prednisolone, mg/dL</td>
<td>3.2 (2.2)</td>
<td>9.9 (7.4)</td>
<td>5.5 (5.7)</td>
<td>.05</td>
</tr>
<tr>
<td>Creatinine, mg/dL</td>
<td>1.91 (0.95)</td>
<td>1.70 (0.73)</td>
<td>1.89 (1.01)</td>
<td>NS</td>
</tr>
<tr>
<td>BUN, mg/dL</td>
<td>34.3 (17.2)</td>
<td>32.3 (16.4)</td>
<td>29.8 (16.7)</td>
<td>NS</td>
</tr>
<tr>
<td>CRP, mg/L</td>
<td>1.33 (2.33)</td>
<td>0.66 (1.08)</td>
<td>1.39 (2.00)</td>
<td>NS</td>
</tr>
<tr>
<td>Hemoglobin, g/dL</td>
<td>12.0 (1.4)</td>
<td>12.2 (1.9)</td>
<td>12.0 (1.7)</td>
<td>NS</td>
</tr>
</tbody>
</table>

Values are shown in mean ± SD.

**Quantitative RT-PCR**

A total of 2 x 10^6 monocytes in a 6-well plate pretreated with or without dexamethasone and rapamycin as indicated were stimulated for 8 hours with 100 ng/mL LPS, and total RNA was extracted in TRIzol (Invitrogen). cDNA was generated by Superscript II (Invitrogen) as suggested by the manufacturer. mRNA levels were determined by TaqMan Gene Expression Assays for IL-12p40, IL-10, and 18S rRNA (Applied Biosystems) on an ABI Prism 7000 in a multiplex PCR. mRNA levels were normalized to 18S rRNA.

**Reporter gene assays**

The reporter construct for NF-κB was from Stratagene. p65 transactivation domain (TAD) and Gal4-Luc plasmids were a kind gift of Neil Perkins. In all experiments, a Renilla luciferase construct was cotransfected to normalize expression. The reporter plasmids were transfected in THP-1 cells with Lipofectamine LTX and Plus Reagent for 24 hours according to the manufacturer’s instructions (Invitrogen). Mouse embryonic fibroblasts were transfected with Lipofectamine for 3 to 5 hours. Afterward, the cells were treated with rapamycin and LPS as indicated for additional 20 hours. Lysates were prepared using passive lysis buffer (Promega), and luciferase assays were performed according to the manufacturer’s instructions (Promega).

**LPS shock model**

Rapamycin was dissolved at 16.8 μg/mL in dimethyl sulfoxide and the stock solution was further diluted to 150 μg/mL with phosphate-buffered saline for injection. Dexamethasone was dissolved in dimethyl sulfoxide at 12.5 μg/mL. LPS from E coli 0111:B4 was from Sigma-Aldrich (#L2630). Male C57BL/6 mice (8 weeks) were injected intraperitoneally with 1.5 mg/kg per day rapamycin or vehicle for 2 consecutive days. On the day of the LPS challenge, some groups were additionally treated with 300 μg/kg dexamethasone subcutaneously or vehicle; and after 30 minutes, mice were challenged intraperitoneally with 20 mg/kg or 10 mg/kg LPS as indicated. Survival was monitored twice daily for 156 hours. All animal experiments were performed according to the institutional ethics committee and the Austrian laws (GZ 68.205/0204-C/GT/2007 and GZ 68.205/0053-II/10b/2008).

**Statistics**

Results are expressed as mean ± SEM. Student t test was used to detect statistical significance. Patient cytokine levels were compared with one-way analysis of variance and Dunnett post test.

**Results**

Hyperactivation of the inflammatory immune response in rapamycin-treated kidney transplant recipients

Our previous results indicated that rapamycin hyperactivates the inflammatory immune response in vitro in humans and in vivo in mice.²⁶,²⁷ We confirmed in human monocytes that rapamycin...
strongly enhanced the production of IL-12p40, IL-12p70, and TNF-α, whereas production of IL-10 was blocked (Figure 1A). To substantiate these results ex vivo, we analyzed the production of inflammatory cytokines in whole blood from stable renal transplant recipients treated with rapamycin, CsA, or FK506 along with MMF and prednisolone. Apart from the steroid dose of FK506 patients, the patient characteristics were similar between the groups (Table 1). Remarkably, patients on rapamycin were exceptionally susceptible to mount a profound proinflammatory response after ex vivo LPS stimulation reflected by a significantly higher production of the inflammatory markers IL-12p40, IL-6, TNF-α, and IL-1β (Figure 1B). Moreover, the anti-inflammatory cytokine IL-10 was significantly suppressed in these patients compared with FK506-treated patients (Figure 1B). Ex vivo addition of rapamycin to whole blood from CsA- or FK506-treated patients, but not MMF or CsA, interferes with mTOR inhibition. PBMCs treated with the indicated concentrations of (A) Dex, (B) MMF, or (C) CsA for 30 minutes were incubated with 100 nM rapamycin (Rap) or medium and then stimulated with 100 ng/mL LPS. IL-12p40 and IL-10 in cell-free supernatants were assessed after 20 hours. Data are mean ± SEM of 5 independent experiments. *P < .05. **P < .01. n.s. indicates not significant. (D) PBMCs were treated with 25 nM Dex and/or 100 nM Rap and then stimulated with 10 μg/mL OKT-3 as indicated. IFN-γ and IL-2 were determined in the supernatant after 24 hours. Data are mean ± SEM of 3 independent experiments. *P < .05. (E) T cells were stimulated with 10 ng/mL OKT-3 and 100 nM Rap and/or 25 nM Dex as indicated. Proliferation was measured on days 2 and 3 and is expressed as the means of triplicates of 2 independent donors.

A

B

C

D

E

Figure 2. Dexamethasone (Dex), but not MMF or CsA, interferes with mTOR inhibition. PBMCs treated with the indicated concentrations of (A) Dex, (B) MMF, or (C) CsA for 30 minutes were incubated with 100 nM rapamycin (Rap) or medium and then stimulated with 100 ng/mL LPS. IL-12p40 and IL-10 in cell-free supernatants were assessed after 20 hours. Data are mean ± SEM of 5 independent experiments. *P < .05. **P < .01. n.s. indicates not significant. (D) PBMCs were treated with 25 nM Dex and/or 100 nM Rap and then stimulated with 10 μg/mL OKT-3 as indicated. IFN-γ and IL-2 were determined in the supernatant after 24 hours. Data are mean ± SEM of 3 independent experiments. *P < .05. (E) T cells were stimulated with 10 ng/mL OKT-3 and 100 nM Rap and/or 25 nM Dex as indicated. Proliferation was measured on days 2 and 3 and is expressed as the means of triplicates of 2 independent donors.
patients similarly augmented IL-12p40 and suppressed IL-10 expression (data not shown). Interestingly, IL-12p40 production significantly correlated with the dose of prednisone only in CsA- and FK506-treated patients but not in rapamycin-treated patients (Figure 1C). These results establish that rapamycin-treated kidney transplant patients display a profound proinflammatory profile on LPS activation compared with CNI-treated patients.

Interference of rapamycin and other immunosuppressants in PBMCs

As therapeutic principle, mTOR inhibition is clinically applied with other immunosuppressive and anti-inflammatory drugs to enable an efficient immunosuppression. As we observed a powerful capability of rapamycin-treated patients to mount a proinflammatory response in the presence of MMF or GC, we investigated whether these immunosuppressants are able to interfere with the immunomodulatory capacity of rapamycin at the cellular level. Freshly isolated human PBMCs were treated with different clinically relevant (2.5 and 25nM) concentrations and a supramaximal dose (250nM) of dexamethasone.39 Dexamethasone effectively suppressed IL-12p40 production in LPS-stimulated PBMCs while leaving the anti-inflammatory cytokine IL-10 largely unaffected (Figure 2A). Strikingly, dexamethasone, at clinically relevant doses, was not able to block the rapamycin-induced enhanced production of IL-12p40, whereas only a supramaximal dose of dexamethasone inhibited the proinflammatory effects of rapamycin (Figure 2A). We obtained similar data, when mTOR was inhibited with 10nM rapamycin (data not shown). These results suggested that the mTOR pathway is connected with GR signaling.

As expected, MMF, which inhibits DNA synthesis, did not modify LPS-stimulated cytokine secretion of IL-12p40/IL-10 and did not significantly alter the proinflammatory effects of rapamycin in PBMCs (Figure 2B). Treatment with CsA resulted in a statistically nonsignificant trend to down-regulate IL-12p40 and increase IL-10 production of LPS-activated PBMCs (Figure 2C). Moreover, CsA was not able to affect the proinflammatory phenotype of rapamycin-treated PBMCs (Figure 2C).

However, testing the immunosuppressive potency of GC and rapamycin after T-cell receptor activation, we observed that treatment with dexamethasone and rapamycin synergistically suppressed IFN-γ and IL-2 secretion after OKT-3 stimulation (Figure 2D), and both drugs also synergistically inhibited T-cell proliferation (Figure 2E). These results demonstrate that rapamycin specifically prevents the anti-inflammatory effects of GC in PBMCs, but both drugs act in a synergistic immunosuppressive manner.
mTOR inhibition prevents the anti-inflammatory effect of dexamethasone in human monocytes

To specifically allocate the observed reciprocal influence of rapamycin and dexamethasone on inflammatory cytokines to a distinct cell type in PBMCs, we assessed purified human monocytes, the cardinal inflammatory cells in human blood. Dexamethasone and rapamycin did not significantly affect apoptosis rates in LPS-treated monocytes (data not shown). Remarkably, rapamycin augmented IL-12p40, TNF-α, and IL-1β production in LPS-stimulated monocytes despite the presence of clinically relevant doses of the glucocorticoid (Figure 3A-C). Again, only high doses of dexamethasone prevented the proinflammatory activity of rapamycin (Figure 3A-B), indicating that rapamycin and dexamethasone might modulate similar downstream signaling pathways, whereas MMF and CNI did not significantly modulate cytokine production (data not shown). Moreover, rapamycin potently inhibited IL-10, and also the anti-inflammatory chemokine MCP-1, which could not be rescued by addition of dexamethasone (Figure 3D-E). As DCs are the major antigen-presenting cells that link innate with adaptive immunity, we wanted to assess whether inhibition of mTOR is able to overcome the anti-inflammatory effects of GCs also in this cell compartment. Using freshly isolated myeloid DCs, we found a similar conspicuous regulation of IL-12p40 production by rapamycin and dexamethasone (Figure 3F). These results suggest that the antagonism of mTOR and GR at the cellular level occurs both in monocytes and peripheral myeloid DCs.

Rapamycin reestablishes a potent Th1-polarizing capacity of dexamethasone-treated monocytes

Inhibition of mTOR in monocytes promotes the differentiation of T helper 1 (Th1) cells,27 whereas glucocorticoids are known to interfere with the Th1-polarizing potency of TLR-activated cells.40 Therefore, we compared the ability of LPS-stimulated monocytes treated with rapamycin and dexamethasone to prime CD4+ Th1 responses. Whereas rapamycin-treated cells strongly enhanced the production of IFN-γ and the differentiation of CD4+ Th1 cells, dexamethasone-treated monocytes suppressed Th1 priming (Figure 3G-H). Strikingly, rapamycin reverted the suppressive effects of dexamethasone-treated cells and reestablished strong IFN-γ production and Th1 polarization (Figure 3G-H). We conclude that mTOR inhibition in monocytes potently promotes Th1 polarization of CD4+ T cells despite the presence of dexamethasone.

mTOR and the GR differentially regulate the activation of NF-κB in monocytes

To further address the molecular targets responsible for the observed reciprocal regulation of the proinflammatory response, we used pharmacologically distinct agents to modulate the mTOR pathway and the GR. Indeed, the mTOR inhibitor Torin-1 was able to enhance IL-12p40 production despite the presence of dexamethasone (Figure 4A) and, moreover, blocked IL-10 production in human monocytes (Figure 4B). On the other hand, treatment of monocytes with hydrocortisone similar to dexamethasone did not prevent rapamycin-induced hyperproduction of IL-12p40 (Figure 4C), whereas IL-10 was not modulated by hydrocortisone (Figure 4D). Together, these results indicate that the proteins mTOR and the GR directly mediate the reciprocal effects of the inhibitors on inflammatory cytokine production.

To gain insight if the interference of mTOR and the GR on inflammatory cytokine production is mediated via transcriptional processes, we isolated mRNA from LPS-treated monocytes that were treated with rapamycin and/or dexamethasone. Although dexamethasone inhibited IL-12p40 mRNA in LPS-stimulated cells, clinical relevant doses of dexamethasone did not interfere with the proinflammatory effect of mTOR inhibition in these cells (Figure 5A). Dexamethasone did not affect IL-10 mRNA production and could not reverse the potent suppression of IL-10 mRNA induced by rapamycin (Figure 5B). Inhibition of mTOR augments the activation of NF-κB,27 whereas dexamethasone has potent inhibitory effects on NF-κB activity.51,42 Therefore, we examined whether mTOR and the GR might reciprocally interact with NF-κB. Although dexamethasone completely suppressed NF-κB activation in LPS-stimulated monocyte THP-1 cells, dexamethasone could no longer repress this transcription factor in the presence of...
Rapamycin blocked NF-κB activation when mTOR was inhibited (Figure 5C). Only at a supramaximal dose, dexamethasone blocked NF-κB activation when mTOR was inhibited (Figure 5C). Next, we analyzed rapamycin- and dexamethasone-dependent NF-κB activation in Tsc2−/−murine embryonic fibroblasts, which display augmented mTOR signaling and are therefore refractory to LPS-induced NF-κB activation27 (Figure 5D). Although dexamethasone decreased NF-κB in LPS-stimulated cells, dexamethasone did not block rapamycin-induced NF-κB hyperactivation, suggesting that the anti-inflammatory action of the GR involves the activation of mTOR signaling (Figure 5D). The transactivation domain (TAD) of p65 recruits specific cofactors to enhance the transcriptional process.43 Interestingly, p65(TAD) was hyperactivated when mTOR was inhibited in LPS-stimulated THP-1 cells, whereas dexamethasone could not decrease this activity either alone or in the presence of rapamycin, suggesting that the TAD of p65 is not reciprocally regulated by mTOR and the GR (Figure 5E). Collectively, these results demonstrate that the potent inhibitory effects of rapamycin on the proinflammatory transcription factor NF-κB are abrogated by rapamycin in monocytes, indicating that a major part of the reciprocal regulation of proinflammatory cytokines by mTOR and the GR are mediated at the level of NF-κB signaling.

Rapamycin mediates proinflammatory effects via the GR-sensitive JNK signaling pathway

To further dissect the molecular mechanisms apart from NF-κB that might be modulated by mTOR and the GR, we investigated whether dexamethasone is able to directly interfere with mTOR signaling. Dexamethasone did not considerably affect the phosphorylation status of S6 or 4E-BP1, 2 downstream mediators of mTOR, in monocytes or THP-1 cells after 30 minutes of LPS stimulation (Figure 6A–B). In contrast, dexamethasone blocked the phosphorylation of c-Jun (Figure 6B), an essential transcription factor subunit important for IL-12p40 production, whereas the mitogen-activated protein kinases Erk-1/2 and p38 were not modulated either by rapamycin or dexamethasone (Figure 6A–B). Recent data demonstrated a selective enhancement of JNK activity in mTOR-inhibited monocytes independent of c-Jun phosphorylation.27 Consistent with these results, SP600125, a specific inhibitor of JNK, completely abolished the enhanced production of IL-12p40, IL-23, and TNF-α by rapamycin (Figure 6C). To identify the underlying molecular mechanism explaining how increased JNK activity on mTOR blockade may lead to enhanced transcriptional activity, we directly assessed the nuclear levels of c-Jun. Rapamycin increased the nuclear levels of c-Jun, whereas dexamethasone prevented the effects of mTOR inhibition (Figure 6D). Hence, one molecular mechanism contributing to the proinflammatory action of rapamycin is the selective enhancement of JNK activity leading to increased nuclear c-Jun levels on TLR engagement. However, the additional usage of dexamethasone to rapamycin- and SP600125-treated cells further down-regulated IL-12p40 production after 24 hours to a level comparable with dexamethasone-treated cells.
only (Figure 6E), indicating that dexamethasone may exert additional effects to affect IL-12p40 expression. Therefore, we analyzed whether long-term treatment with dexamethasone might modulate the mTOR pathway. Strikingly, we observed that LPS stimulation of THP-1 cells for 24 hours up-regulated TSC2 protein levels (Figure 6F). Dexamethasone completely blocked the LPS-induced increase of TSC2 levels and led to a concurrent activation of the mTOR pathway as shown by phosphorylation of S6 (Figure 6F). Activation of S6 negatively depended on TSC2 as knockdown of TSC2 increased S6 phosphorylation under all conditions tested (Figure 6F). These results were also observed in LPS-stimulated monocytes, where long-term treatment with dexamethasone increased S6 activity as well, whereas rapamycin abrogated the positive input signal from the GR to the mTOR pathway (Figure 6G). These results reveal a novel link between the GR and the mTOR pathway at the level of TSC2 and suggest that long-term treatment with dexamethasone may activate the mTOR signaling to regulate the inflammatory response.

**Rapamycin overrides the beneficial effects of dexamethasone in a murine sepsis model**

After having established that mTOR and the GR reciprocally regulate inflammatory cytokine production in innate immune cells in vitro and ex vivo, we wondered whether the anti-inflammatory potency of GCs can be overcome by rapamycin in a murine LPS shock model. Recently, it has been shown that rapamycin augments lethality and proinflammatory cytokine production in LPS-treated C57BL/6 mice. Similarly, we also observed that rapamycin significantly increased mortality, when mice were injected with an LD50 LPS dose (Figure 7A), whereas dexamethasone completely prevented LPS-induced mortality (Figure 7A). Remarkably, dexamethasone was not able to rescue rapamycin-treated animals from death (Figure 7A), suggesting that rapamycin overrides the beneficial effects of GC also in a relevant inflammatory disease model in vivo. Whereas rapamycin inhibited IL-10 production in septic mice in vivo, dexamethasone did not reestablish IL-10 expression in mTOR-inhibited animals (Figure 7B). In addition, whereas dexamethasone completely repressed IL-12p70 production, rapamycin still allowed expression of bioactive IL-12p70 when the GR was activated in septic mice (Figure 7B). These results show that rapamycin enhances lethality in an LPS-shock model in vivo despite concurrent treatment with an effective anti-inflammatory intervention.

**Discussion**

The molecular mode of action of medically approved drugs in transplantation medicine is still surprisingly ill defined, in particular when used in combination, but is mandatory for the assessment of drug-related risks and also novel therapeutic avenues. Hence, the elucidation of the effects of currently used immunosuppressive agents and regimens on the innate immune system is crucial as the evidence of the importance of monocytes and DCs for allograft
promoted Th1 responses even in the presence of the glucocorticoid. This mutual regulation of proinflammatory versus anti-inflammatory functions was dependent on mTOR and the GR as the mTOR inhibitor Torin1 or hydrocortisone, respectively, mimicked the effects of rapamycin and dexamethasone. Rapamycin and dexamethasone are known to have transcriptional-dependent and -independent effects on gene regulation; however, both drugs reciprocally modulated the mRNA levels of IL-12p40, indicating that mTOR and the GR modulate transcriptional events in human monocytes. Moleculally, IL-12p40 hyperactivation during mTOR inhibition is mediated by increased NF-κB activity, and dexamethasone could not inhibit this enhanced activity under physiologic doses. In addition, we found that rapamycin promoted JNK signaling by increasing nuclear c-Jun levels, whereas dexamethasone diminished c-Jun in the nucleus in the presence of mTOR inhibition.

A connection between the mTOR pathway and the GR has been established in many cell lines. In these cells, activation of the GR by GC induces the expression of RTP801 (also known as REDD1), which inhibits mTOR signaling. However, we have shown in innate immunocompetent cells that long-term treatment with GC activates mTOR signaling in LPS-stimulated monocytes by reducing the expression of TSC2. To our knowledge, these results are the first to show that the protein levels of TSC2 can be directly altered via GC and/or via the inflammatory stimulus LPS. Moreover, LPS-stimulated PBMCs of kidney transplant tuberous sclerosis patients, who have steady-state activation of the mTOR pathway because of mutations in TSC1 or TSC2, show an diminished ability to produce proinflammatory cytokines compared with control patients who could be restored after conversion to rapamycin despite the presence of GC. These data lend further support to the concept that the mTOR pathway is a central control unit of inflammatory responses.

Clinically, it has been observed that distinct inflammatory side effects of mTOR inhibitors, including pneumonitis and glomerulonephritis, cannot be ameliorated with GC. For instance, mTOR inhibitor-induced pneumonitis requires the discontinuation of the mTOR inhibitor despite the concurrent use of GC. Moreover, myeloid DCs have a proinflammatory phenotype in rapamycin-treated patients despite concurrent prednisone therapy. Our current results that clinically applicable doses of GC cannot ameliorate the inflammatory events observed with mTOR inhibitor therapy may provide one molecular rationale for this unusual phenomenon. Moreover, they support the notion that discontinuation of the mTOR inhibitor in such events might be favorable rather than escalating the steroid.

In conclusion, we could show in this study that the GR is connected with the mTOR pathway in human monocytes to modulate inflammatory responses. The potent anti-inflammatory effects of dexamethasone were rendered ineffective in the presence of rapamycin, resulting in sustained production of proinflammatory cytokines. These data not only reveal a novel basic regulatory principle in innate immune cells but also may allow to better understand the interaction of currently used immunosuppressants within the innate immune cell compartment and finally may allow optimizing immunosuppressive protocols.

Acknowledgments

The authors thank Barbara Vodenik and Margarethe Merio for excellent technical assistance.
T.W. and M.D.S. were supported by the Else-Kröner-Fresenius-Stiftung. C.L. and M.M. were supported by the Austrian Science Foundation FWF (SFB F28) and the Austrian Federal Ministry for Science and Research (GEN-AU III Austromouse).

References


26. Haidinger M, Poglitsch M, Geyeregger R, et al. Phagocytosis and wrote the manuscript; M.P., C.K., K.K., C.L., and M.R. performed experiments; M. Haidinger collected clinical samples; M. Hengstschlager, M.M., G.J.Z., and W.H.H. gave technical support; and M.D.S. wrote the manuscript and supervised the project.

Conflict-of-interest disclosure: The authors declare no competing financial interests.

Correspondence: Marcus D. Saemann, Department of Internal Medicine III, Division of Nephrology & Dialysis, Medical University Vienna, Währinger Gürtel 18-20, A-1090 Vienna, Austria; e-mail: marcus.saemann@meduniwien.ac.at.

From www.bloodjournal.org by guest on November 13, 2017. For personal use only.


45. Turnquist HR, Cardinal J, Macedo C, et al. mTOR and GSK-3 shape the CD4+ T-cell stimulatory and differentiation capacity of myeloid DCs after exposure to LPS. *Blood.* 2010;115(23):4758-4769.


Inhibition of mTOR blocks the anti-inflammatory effects of glucocorticoids in myeloid immune cells

Thomas Weichhart, Michael Haidinger, Karl Katholnig, Chantal Kopecky, Marko Poglitsch, Caroline Lassnig, Margit Rosner, Gerhard J. Zlabinger, Markus Hengstschläger, Mathias Müller, Walter H. Hörl and Marcus D. Säemann