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Dual Inhibition of Rip2 and IRAK1/4 Regulates IL-1β and IL-6 in Sarcoidosis Alveolar Macrophages and Peripheral Blood Mononuclear Cells

Jaya Talreja,* Harvinder Talwar,* Nisar Ahmad,* Ruchi Rastogi,* and Lobelia Samavati*†

Sarcoidosis is a multisystem granulomatous disease of unknown etiology that primarily affects the lungs. Our previous work indicates that activation of p38 plays a pivotal role in sarcoidosis inflammatory response. Therefore, we investigated the upstream kinase responsible for activation of p38 in sarcoidosis alveolar macrophages (AMs) and PBMCs. We identified that sustained p38 phosphorylation in sarcoidosis AMs and PBMCs is associated with active MAPK kinase 4 but not with MAPK kinase 3/6. Additionally, we found that sarcoidosis AMs exhibit a higher expression of IRAK1, IRAK-M, and receptor interacting protein 2 (Rip2). Surprisingly, ex vivo treatment of sarcoidosis AMs or PBMCs with IRAK1/4 inhibitor led to a significant increase in IL-1β mRNA expression both spontaneously and in response to TLR2 ligand. However, a combination of Rip2 and IRAK-1/4 inhibitors significantly decreased both IL-1β and IL-6 production in sarcoidosis PBMCs and moderately in AMs. Importantly, a combination of Rip2 and IRAK-1/4 inhibitors led to decreased IFN-γ and IL-6 and decreased percentage of activated CD4+CD25+ cells in PBMCs. These data suggest that in sarcoidosis, both pathways, namely IRAK and Rip2, are deregulated. Targeted modulation of Rip2 and IRAK pathways may prove to be a novel treatment for sarcoidosis. *The Journal of Immunology, 2016, 197: 1368–1378.
In the current study, we investigated the role of the upstream kinases IRAK1 and Rip2 in p38 activation in sarcoidosis. In an ex vivo model of AMs and PBMCs, we show that AMs and PBMCs of patients with sarcoidosis exhibit higher expression for IRAK1 and Rip2. Furthermore, we found that increased p38 activation in sarcoidosis is associated with MAPK kinase (MKK) 4 activation. Finally, we assessed the effect of IRAK1/4 and Rip2 inhibitors on IL-1β and IL-6 production and the activation of p38 in sarcoidosis AMs and PBMCs. Application of IRAK1/4 inhibitor or Rip2 inhibitors alone did not inhibit the IL-1β and IL-6 production, whereas a combination of IRAK1/4 and Rip2 inhibitors significantly reduced the synthesis of these cytokines and the phosphorylation of p38. Surprisingly, dual inhibition of IRAK1/4 and Rip2 modulated activated T cell, IL-6, and IFN-γ production in sarcoidosis PBMCs.

Materials and Methods

Chemicals

Chemicals were purchased from Sigma-Aldrich (St. Louis, MO) unless specified otherwise. All ligands, LPS, and Pam3CysSk4 (PAM) were purchased from InvivoGen (San Diego, CA). IRAK1/4 inhibitor was purchased from Calbiochem (San Diego, CA). Gefitinib (Rip2 inhibitor) was purchased from InvivoGen. Abs against total p38 and phospho-p38 were purchased from Cell Signaling Technology (Beverly, MA). The Abs used for immunostaining CD14 and CD25 were pp38-FITC, CD14-PE, and anti-rabbit IgG Abs were purchased from Cell Signaling Technology. The anti-human Abs used for flow cytometry were pp38-FITC, CD14-PE, CD4-FITC, CD25-PE, and purified CD3 and were purchased from BD Biosciences (San Jose, CA). The Abs used for immunostaining CD14 Alexa 488 and pp38 Alexa 594 were purchased from Molecular Probes (Grand Island, NY).

Study design

The Committee for Investigations Involving Human Subjects at Wayne State University approved the protocol for obtaining alveolar macrophages by BAL and blood by phlebotomy from control subjects and patients with sarcoidosis. Sarcoidosis diagnosis was based on the American Thoracic Society’s criteria (26) and the association of Sarcoidosis and other Granulomatous Disorders statement (26). The criteria for enrollment in the diseased group were: 1) a compatible clinical/radiographic picture consistent with sarcoidosis; 2) histologic demonstration of noncaseating granulomas on the tissue biopsy; and 3) exclusion of other diseases capable of producing a similar histologic or clinical picture, such as fungus and mycobacteria. Subjects excluded: 1) were smokers; 2) had a history of hepatitis or HIV infection; and 3) had positive HIV or hepatitis test.

RNA extraction and quantitative real-time RT-PCR.

Total RNA was extracted using TRIzol reagent (Life Technologies) and reverse transcribed using the ABI Reverse Transcription System (Life Technologies). The primers (targeting IL-1β and a reference gene, beta-actin) were used to amplify the corresponding cDNA by using iQ SYBR Green Supermix (Bio-Rad). qPCR amplification was performed in a total volume of 20 μl containing 2 μl each cDNA preparation and 20 μl primers (Invitrogen). The PCR amplification protocol was as follows: 95°C for 10 min, followed by 40 cycles of 95°C for 15 sec, 60°C for 60 sec, and 72°C for 30 sec. PCR products were electrophoresed on 1% agarose gel and visualized by ethidium bromide staining.

Flow cytometry and cell surface immunostaining.

PBMCs from control subjects or subjects with sarcoidosis were isolated, cultured, and, after appropriate treatment, were stained for the cell surface markers using fluorescences-labeled Abs for CD4, CD25, and CD14. After cell-surface staining with CD14, cells were permeabilized and stained concomitantly with phospho-p38. Flow cytometry was performed on a BD LSRII SORP (High Sensitivity), and data analysis was performed using FlowJo software (Tree Star, Ashland, OR). Samples were gated on cells using forward light scatter/side scatter (SSC), and doublet discrimination was performed to identify singlets using SSC-width versus SSC-area. The flow cytometry work was done at the Microscopy, Imaging and Cytometry Resources Core at The Karmanos Cancer Institute, Wayne State University.

Immunofluorescent staining.

Intracellular expression of pp38 in sarcoidosis AMs or PBMCs was visualized by immunofluorescence staining. AMs (1 × 10^6) or PBMCs (2 × 10^5) were allowed to adhere on chamber slides overnight. The cells were washed briefly with PBS and fixed with 1% Triton X-100 and immunostained with anti-human CD14 Alexa 488 and pp38 Alexa 594 overnight at 4°C. The next day, the cells were washed three times with PBS for 5 min, and the slide was mounted with a drop of Fluoromount-Gold antifade reagent with DAPI (Invitrogen). The slide was examined using an Axiovert 40 CFL fluorescence microscope (Carl Zeiss MicroImaging).

Protein extraction and immunoblotting.

Cells were harvested after the appropriate treatment and washed twice with PBS. Total cellular proteins were extracted by addition of RIPA buffer containing a protease inhibitor mixture and antiphosphatase I and II (Sigma-Aldrich). Protein concentration was measured by the BCA assay (Thermo Scientific). Equal amounts of proteins (10–25 μg) were mixed/1 (v/v) with 2× sample buffer (5% glycerol, 4% 2-ME, 0.05% bromophenol blue, and 1.25 mol Tris-HCl [pH 6.8]) and fractionated on a 10% NaDodSO4-polyacrylamide gel. Proteins were transferred onto a polyvinylidene difluoride membrane (Amersham GE). Images were captured on Hyblot CL film (Denville Scientific, Metuchen, NJ) using a bioimaging analyzer. Data analysis was performed using ImageJ software (Wayne Rasband, National Institutes of Health).

BAL and the preparation of cell suspensions.

BAL was collected during bronchoscopy after administration of local anesthesia and before tissue biopsies. Briefly, a total of 150–200 ml sterile saline solution was injected via fiberoptic bronchoscopy; the BAL fluid was retrieved, measured, and centrifuged. Cells recovered from the BAL fluid were filtered through a sterile gauze pad and washed three times with PBS, resuspended in endotoxin-free RPMI 1640 medium (HyClone) supplemented with 1-glutamine (Life Technologies), penicillin/streptomycin (Life Technologies), and 1% FCS (HyClone), and then counted. BAL cells were cultured on adherent plates for 1 h at 37°C in air containing 5% CO2. Nonadherent cells were removed by aspiration adherent cells, washed three times, and used as AMs. Viability of these populations was routinely >97%, and by morphologic criteria, the adherent cells were >98% AMs.

Isolation of PBMCs.

PBMCs were isolated from heparinized blood using Ficoll-Histopaque (Sigma-Aldrich) density gradient separation followed by washing twice with PBS. Cell suspension was made in endotoxin-free RPMI 1640 medium (HyClone) supplemented with 1-glutamine (Life Technologies), penicillin/streptomycin (Life Technologies), and 10% FCS (HyClone). Cells were cultured in 12-well plates for different time periods.

Cell viability

Cell viability was measured using the MIT assay as described previously (27). Cells equivalent to 1 × 10^5 ml^-1 were seeded in 96-well cell-culture plates treated in the presence and absence of inhibitor/ligands based on experimental design. Absorbance was measured at 550 nm. Relative cell viability was calculated according to the formula: cell viability = absorbance experimental/experimental control × 100.

ELISA.

The levels of IL-1β, IL-6, and IFN-γ in the conditioned medium were measured by ELISA according to the manufacturer’s instructions (ELISA DuoKits; R&D Systems, Minneapolis, MN).

Results and discussion

Finally, we assessed the effect of IRAK1/4 and Rip2 modulated activated T cell, IL-6, and IFN-γ production in sarcoidosis PBMCs.

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Statistical analyses. Statistical analyses were performed using SPSS software, version 22.0 (SPSS, Chicago, IL). One-way ANOVA test and post hoc repeated-measures comparisons (least significant difference) were performed to identify differences between groups. ELISA results were expressed as mean ± SEM. For all analyses, two-tailed p values ≤ 0.05 were considered significant.

Results
Concordance in p38 activation between circulating CD14+ cells and AMs in sarcoidosis

Previously, we have shown that sarcoidosis AMs and BAL exhibit sustained p38 activation at baseline and in response to stimulation with TLR4 ligands (20). To test the hypothesis that PBMCs of patients with sarcoidosis exhibit similar inflammatory phenotypes, we simultaneously assessed p38 activation in PBMCs and AMs in patients with sarcoidosis. All patients were ambulatory outpatients, and most patients had radiologic stage 2 sarcoidosis (Table I). Diagnosis of sarcoidosis was established based on American Thoracic Society criteria, and all samples were examined for microbiology including mycobacteria species. CD14 is a general marker for macrophages, monocytes, and dendritic cells (28). Previously, it has been shown that CD14+ monocytes resemble tissue macrophages and are potent APCs, and they may play a role in sarcoidosis pathology (29). PBMCs from subjects with sarcoidosis and control subjects were concomitantly stained for CD14 and the active form of p38 (pp38) and analyzed via flow cytometry. As shown in Fig. 1A and 1B, the percentage of CD14+ cells in sarcoidosis was higher (55%) in a representative sample than in healthy control subjects, which show ~18% CD14+ monocytes. Similarly, double-positive CD14+ cells and phospho-p38 (20%) were significantly higher as compared with healthy control subjects (5%). When the percentage of phospho-p38 was normalized to the percentage of total CD14, sarcoidosis PBMCs exhibited ~36% double-positive cells, whereas healthy control PBMCs showed ~27%. Fig. 1C shows the box plot of cumulative values of eight patients and eight control subjects. These data indicate that PBMCs of patients with sarcoidosis exhibit significantly higher CD14 and phospho-p38–positive cells. Furthermore, we analyzed the baseline activation of p38 in PBMCs and AMs from the same patients. Fig. 1D shows the Western blots detecting pp38 in both sarcoidosis PBMCs and AMs. We detected higher p38 activation in AMs as compared with PBMCs. Similar results were obtained when we performed immunohistochemistry in AMs and PBMCs of patients with sarcoidosis. Supplemental Fig. 1 shows representative immunofluorescence staining using anti CD14 Ab and Ab against phospho-p38 in AMs (Supplemental Fig. 1A) and PBMCs (Supplemental Fig. 1B). Fig. 1E summarizes the results of Western blots of phospho-p38 both in PBMCs and AMs from 10 control subjects and 12 subjects with sarcoidosis. These results indicate that there is a concordance between sarcoidosis PBMCs and AMs in terms of active p38, but sarcoidosis AMs exhibited higher (2- to 3-fold) p38 activation as compared with PBMCs. These results are in line with prior studies that CD14 expression is higher in sarcoidosis AMs and PBMCs (20, 30).

Sustained activation of p38 in sarcoidosis is associated with activated MKK4 but not with MKK3/6
The identification of the predominant kinase(s) with major contribution in p38 activation and determining the level of dysregulation of upstream kinase(s) in sarcoidosis is critical. To model the inflammatory pathway in sarcoidosis, we challenged cells with TLR2 and TLR4 ligands. The rationale for such activation was that previously, it has been shown that aberrant TLR2 and TLR4 signaling may play role in sarcoidosis pathology (31, 32). Several upstream kinases, including apoptosis signal-regulating kinase-1 (ASK1), MKK3/6, and MKK4, can activate p38 (33, 34). We set up the experiments to identify upstream kinases(s), which plays a major role in the p38 activation in sarcoidosis. To identify the potential role of these kinases, we isolated AMs or PBMCs of patients with sarcoidosis and assessed the phosphorylation of MKK4 and MKK3/6 as well as ASK1. BALs were cultured on adherent plates and allowed to attach for 1 h. They then were challenged with LPS (1 ng/ml) or PAM (100 ng/ml) for 30 min or left untreated in media. Immunoblotting was performed using phospho-specific Abs against the active forms of p38, MKK3/6, and MKK4. As shown in Fig. 2A, AMs of patients with sarcoidosis exhibited higher phospho-p38 at the baseline and in response to challenge with TLR2 or TLR4 agonists. We observed similar results with isolated PBMCs of sarcoidosis patients (Fig. 2B).

Neither sarcoidosis AMs nor PBMCs showed phosphorylation of MKK3/6 (Fig. 2A, 2B) nor ASK1 (data not shown). Instead, we detected an increase of activated MKK4 at baseline and in response to PAM or LPS in sarcoidosis AMs and PBMCs (Fig. 2B). Fig. 2C and 2D represent densitometric values (mean ± SEM) of the phosphorylated form of MKK4 and p38 from 12 different subjects normalized either to β-actin or total p38. These data suggest that AMs exhibited significantly higher pMKK4 as well as phospho-p38 expression as compare with PBMCs.

Active p38 is associated with increased IRAK1 and Rip2 proteins in sarcoidosis AMs and PBMCs

Both IRAK1 and Rip2 kinases play an important role in p38 activation (35). IRAK1 interacts with MyD88 and is upstream of a kinase cascade for which activation subsequently activates MAPks, including p38 and NF-κB, leading to the production of inflammatory mediators (36). Although IRAK1 is well studied in mouse models, its role in human diseases, especially in sarcoidosis, is unclear. To determine expression level of IRAK1 in human cells and its role in inflammatory signaling in sarcoidosis, we used two different TLR ligands, LPS (1 ng/ml), or for TLR2, PAM (100 ng/ml). As shown in Fig. 3A, sarcoidosis AMs exhibit higher expression of IRAK1 at baseline. Similarly, we observed a higher IRAK-M expression in sarcoidosis AMs baseline with no further induction in response to TLR ligands (Fig. 3A). In contrast, AMs of control subjects showed no IRAK-M at baseline, although IRAK-M was induced in response to both TLR ligands (Fig. 3A).

Table I. Subject demographics

<table>
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<tr>
<th>Characteristic</th>
<th>Patients</th>
<th>Control Subjects</th>
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<tbody>
<tr>
<td>Age, y</td>
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<td>BMI</td>
<td>29 ± 10.4</td>
<td>28 ± 3.6</td>
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<td>Gender, n (%)</td>
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<td></td>
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<tr>
<td>Female</td>
<td>27 (77)</td>
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<tr>
<td>Male</td>
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<td>4 (21)</td>
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<td>Race, n (%)</td>
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<td>4 (21)</td>
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</tr>
<tr>
<td>1</td>
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</tr>
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</tr>
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</tr>
<tr>
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<tr>
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<tr>
<td>Multiorgan</td>
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</tr>
<tr>
<td>PPD</td>
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</table>

BMI, body mass index; CXR, chest x-ray; NA, not applicable; PPD, purified protein derivative.
Additionally, we determined the expression for IRAK1 and IRAK-M in PBMCs of subjects with sarcoidosis as well as healthy control subjects. Sarcoidosis PBMCs exhibited higher expression level for IRAK1 as compared with healthy control subjects, but there was no further induction in response to TLR2 challenge (Fig. 3B). Fig. 3C and 3D represent the densitometric values (mean ± SEM) of IRAK1 and IRAK-M in AMs, whereas Fig. 3E and 3F show the densitometric values of IRAK1 and IRAK-M in PBMCs of 6 control subjects and 10 patients with sarcoidosis. Because of the importance of Rip2 in p38 activation (12), we assessed Rip2 protein expression in AMs as well as PBMCs in sarcoidosis and control. A representative blot is shown in Fig. 3G from two sarcoidosis subjects (P1 and P2) and two control subjects (C1 and C2). Fig. 3H shows the cumulative results of densitometric values of Rip2 of 6 control subjects and 10 sarcoidosis subjects. Our data indicate that sustained p38 phosphorylation in sarcoidosis is associated with a higher expression for IRAK1 as well as Rip2 at baseline.

IRAK1/14 inhibitor has no effect on IL-1β and IL-6 production and p38 phosphorylation

There is evidence that IRAKs play a differential role in several inflammatory diseases including, lupus and rheumatoid arthritis.
Because we observed a higher expression of IRAK1 in sarcoidosis AMs and PBMCs, we postulated that IRAK1/4 inhibitors may have a potential role in inflammatory responses associated with sarcoidosis. We investigated the effect of IRAK1/4 inhibitor on the production of IL-1β and IL-6, two major proinflammatory cytokines, in sarcoidosis AMs and PBMCs. First, we determined the dose-dependent inhibitory effect of IRAK1/4 inhibitor in control PBMCs in response to LPS. We found that 20 μmol has an inhibitory effect on LPS mediated IL-6 production (data not shown). Pretreatment of sarcoidosis AMs or PBMCs with IRAK1/4 inhibitor did not decrease IL-1β production at baseline or in response to TLR2 or TLR4 ligands (Fig. 4A, 4B). As shown in Fig. 4C, we observed an enhanced IL-6 production in sarcoidosis AMs after treatment with IRAK1/4 inhibitor at baseline (p < 0.05), but not after challenge with LPS or PAM. Based on our previous work, sustained activation of p38 plays a critical role in sarcoidosis inflammation; hence, we examined the effect of IRAK1/4 inhibitor on p38 phosphorylation both in AMs as well as PBMCs of subjects with sarcoidosis. As shown in Fig. 4D, pretreatment of sarcoidosis AMs with IRAK1/4 inhibitor did not decrease phospho-p38 both at baseline and after challenge with LPS or PAM. In contrast, we observed an increase in p38 phosphorylation after pretreatment of AMs with IRAK1/4 inhibitor and challenge with LPS or PAM. Although pretreatment with IRAK1/4 inhibitor had tendency to increase p38 phosphorylation at baseline and in response to PAM and LPS, it did not meet the statistical significance. This partly was due to a higher variation of phospho-p38 among patients.

Cumulative densitometric values (mean ± SEM) of Western blots from six patients are shown in Fig. 4E.

Combination of IRAK1/4 and Rip2 inhibitors inhibits TLR2-mediated cytokine production in sarcoidosis PBMCs and AMs

Because IRAK1/4 inhibitor did not significantly decrease IL-1β and IL-6 production at baseline or in response to TLR2 ligand and because both adapter proteins (IRAK1 and Rip2) were highly expressed in sarcoidosis AMs, we investigated if the simultaneous inhibition of both pathways effects cytokine production in sarcoidosis. Sarcoidosis AMs and PBMCs were cultured in the presence or absence of inhibitors (IRAK1/4 inhibitor and gefitinib, 1 μmol) for 30 min followed by PAM challenge for 24 h. Conditioned media were assessed for IL-1β and IL-6 production. Fig. 5A shows the effect of IRAK1/4 and Rip2 inhibitors alone or in combination in the presence of PAM on IL-1β production in sarcoidosis AMs. As shown, neither inhibitor alone or in combination completely blocked baseline IL-1β release in AMs, but PAM-induced IL-1β release was inhibited in AMs of subjects with sarcoidosis. Fig. 5B shows that sarcoidosis AMs released a high amount of IL-6 at baseline with a further increase upon stimulation with TLR2 ligand. Pretreatment with a combination of IRAK1/4 inhibitor and gefitinib led to a reduction in baseline as well as PAM-induced IL-6 production (Fig. 5B). Next, we examined the effect of these inhibitors on IL-1β and IL-6 production in PBMCs of patients with sarcoidosis. Fig. 5C shows IL-1β...
production in the conditioned media of cultured PBMCs after 24 h culture at baseline and after challenge with PAM. As shown, sarcoidosis PBMCs exhibited spontaneous release of IL-1β, yet the amount of IL-1β from PBMC was considerably lower as compared with IL-1β released from AMs. Challenged with PAM, PBMCs responded with increased IL-1β production. Although IRAK1/4 inhibitor alone did not inhibit IL-1β production, pretreatment with gefitinib significantly decreased baseline IL-1β production in sarcoidosis PBMCs. Interestingly, a combination of gefitinib and IRAK1/4 inhibitor significantly decreased both baseline and PAM-induced IL-1β production (Fig. 5C). Next, we examined IL-6 production in sarcoidosis PBMCs in response to PAM challenge. Consistent with previous results, we found spontaneous release of IL-6 in the conditioned media of cultured sarcoidosis PBMCs with a significant increase in response to PAM. The combination of IRAK1/4 and Rip2 inhibitors led to a significant decrease in IL-6 production both at baseline and in response to TLR2 activation (Fig. 5D). Data represent mean ± SEM from at least 10 different experiments. We concluded that a combination of gefitinib and IRAK1/4 inhibitor is more effective to inhibit IL-1β and IL-6 production in PBMCs as compared with AMs.

**Effect of IRAK1/4 inhibitor and gefitinib on gene expression and p38 phosphorylation**

Previous work has shown a spontaneous release of IL-1β from sarcoidosis AMs (20, 38, 39), and current data indicate that IRAK1/4 inhibitor does not block IL-1β release in sarcoidosis

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**FIGURE 4.** IRAK-1/4 inhibitor does not inhibit IL-1β, IL-6 production, and p38 phosphorylation in sarcoidosis AMs and PBMCs. AMs or PBMCs of subjects with sarcoidosis were pretreated with IRAK-1/4 inhibitor (20 μmol) for 1 h and stimulated with PAM (100 ng/ml) or LPS (1 ng/ml) for 24 h. The conditioned medium was assessed for IL-1β and IL-6 using ELISA. IRAK1/4 inhibitor did not significantly inhibit either IL-1β or IL-6 production both in sarcoid AMs (A and C) and IL-1β in PBMCs (B). Data represent mean ± SEM from at least six different patients. (D) Sarcoidosis AMs were treated with TLR2 and TLR4 ligands in the presence or absence of IRAK1/4 inhibitor. Cell lysates were subjected to immunoblotting using phospho-p38 and total p38 (equal loading) Abs. IRAK1/4 inhibitor did not decrease p38 phosphorylation in AMs. (*p < 0.05 was considered significant.

**FIGURE 5.** Effect of gefitinib and IRAK1/4 inhibitor on IL-1β and IL-6 synthesis in sarcoid AMs and PBMCs. AMs (A and B) or PBMCs (C and D) were pretreated with combination of IRAK1/4 inhibitor (20 μmol) and gefitinib (1 μmol) for 30 min and then activated with PAM (100 ng/ml) for 24 h. Conditioned media were analyzed for IL-1β and IL-6 via ELISA. Data represent mean ± SEM from at least 10 different patients. *p < 0.05 was considered significant.
ALMs or PBMCs. To determine whether this effect is regulated at the transcriptional level, we used quantitative real-time RT-PCR to evaluate IL-1β mRNA levels. AMs and PBMCs from subjects with sarcoidosis were isolated and cultured for 1 h in the presence or absence of AMs and either gefitinib or IRAK1/4 inhibitor or a combination of both. As shown in Fig. 6A, PAM challenge of sarcoidosis AMs led to an increased expression of IL-1β mRNA (∼10-fold). Gefitinib alone decreased basal IL-1β mRNA expression (p < 0.001). Surprisingly, treatment of AMs with IRAK1/4 inhibitor, even without TLR2 stimulation, led to an exuberant IL-1β mRNA expression (∼80–90-fold). The combination of gefitinib and IRAK1/4 inhibitor blocked baseline as well as TLR2-induced IL-1β mRNA expression (Fig. 6A). Using PBMCs from patients with sarcoidosis under the same conditions, we observed a significant reduction of IL-1β gene expression in response to gefitinib alone or in combination with the IRAK1/4 inhibitor (Fig. 6B). To further elucidate the mechanism behind increased IL-1β mRNA expression in response to IRAK1/4 inhibitor, we evaluated the mRNA levels of Rip2 gene using quantitative real-time RT-PCR. As shown in Fig. 6C, AMs of patients with sarcoidosis responded to TLR2 ligation with an increased expression of Rip2 (25-fold). IRAK1/4 inhibitor alone induced mRNA levels of Rip2 (∼48-fold) similar to its effect on the induction of IL-1β mRNA. In contrast, a combination of IRAK1/4 and Rip2 inhibitors strongly inhibited the mRNA levels of Rip2 after stimulation with PAM (Fig. 6C). Next, we examined the effects of gefitinib and IRAK 1/4 inhibitor on p38 phosphorylation in AMs and PBMCs of patients with sarcoidosis. AMs and PBMCs were cultured in the presence and absence of the inhibitors and challenged with PAM for 30 min. Whole-cell lysates were subjected to immunoblotting to assess p38 phosphorylation. Fig. 6D shows the effect of gefitinib, IRAK1/4 inhibitor and a combination of both inhibitors on TLR2-mediated p38 phosphorylation. The AMs of patients with sarcoidosis exhibited an active form of p38 at baseline, as we previously reported (20). Challenge of sarcoidosis AMs with PAM led to an enhanced p38 phosphorylation. However, pretreatment of AMs with a combination of gefitinib and IRAK1/4 inhibitor significantly reduced p38 activation after PAM challenge. We observed comparable results when experiments were performed with sarcoidosis PBMCs, yet sarcoidosis PBMCs exhibited a significantly lower p38 phosphorylation at baseline (Fig. 6D). Fig. 6E shows the cumulative densitometric values of the ratio pp38/p38 of AMs and PBMCs in 10 patients in the presence and absence of both inhibitors at baseline and in response to PAM.

**Dual inhibition of IRAK4 and Rip2 kinases decreases T cell activation in sarcoidosis**

Activated T cells play a major role in sarcoidosis pathology (40). Hence, we investigated the effect of gefitinib and IRAK1/4 inhibitor on T cell population in sarcoidosis PBMCs. The activation of CD4+ T cells was assessed by determining the percentage of CD4+CD25+ cells in a gated lymphocyte population. PBMCs were cultured either alone or challenged with anti-CD3 (1 μg/ml) in the presence or absence of inhibitors. Fig. 7A shows a representative dot plot of a subject with sarcoidosis. At baseline, 48% of cells express CD4 marker, and among those, 10% were double positive for CD4+CD25+, a marker for T cell activation. A combination of IRAK1/4 inhibitor and gefitinib decreased the percentage of CD4 cells (from 48 to 39%) and the CD4+CD25+ activated T cells to 5% (Fig. 7B). In response to anti-CD3 challenge, a percentage of CD4+ cells increased to 65%, among those double-positive T cells (CD4+CD25+) increased from 10 to 62% (Fig. 7B, 7C). Furthermore, a dual inhibition of Rip2 and IRAK1/4 significantly decreased both the percentage of CD4+ and activated T cells after anti-CD3 challenge from 65 to 42% and 62 to 18%, respectively (Fig. 7D). Fig. 7E shows mean ± SEM of the percentage of CD4+CD25+ cells of five patients at baseline, in response to anti-CD3 treatment and in the presence and absence of both inhibitors. These results indicate that pretreatment with a combination of gefitinib and IRAK1/4 inhibitor decreases significantly the percentage of CD4+CD25+ cells at baseline and in response to anti-CD3 challenge.
IFN-γ and IL-6 play an important role in Th1-mediated immunopathology of sarcoidosis (41). Next, we examined the effect of IRAK1/4 and gefitinib on IFN-γ and IL-6 production in patients with sarcoidosis. PBMCs were cultured either alone or challenged with anti-CD3 (1 μg/ml) in the presence or absence of inhibitors for 96 h. IFN-γ and IL-6 production was assessed in culture supernatants by ELISA. As shown in Fig. 7F, pretreatment of PBMCs with IRAK1/4 and gefitinib resulted in complete inhibition of IFN-γ and IL-6 production. Similarly, pretreatment with a combination of IRAK1/4 inhibitor and gefitinib significantly inhibited anti-CD3-induced IL-6 release in sarcoidosis PBMCs (Fig. 7G). These results suggest that a combination of IRAK1/4 and Rip2 inhibitors is effective in inhibiting activated CD4+ T cells as well as IFN-γ and IL-6 production in sarcoidosis PBMCs. Regulatory T cells (Tregs; Foxp3+ cells) engage in the maintenance of immunological self-tolerance by suppressing active lymphocytes, and they play a role in sarcoidosis pathology (42). We assessed the effect of both inhibitors on CD4+CD25+FOXP3+ subset, because one potential mechanism for reduced IFN-γ and IL-6 production in response to inhibitor could have been the modulatory effect on Tregs. Supplemental Fig. 2 shows that gefitinib and IRAK1/4 inhibitor have no effect on Tregs.

**Discussion**

The exact mechanisms underlying the increased production of Th1 cytokines in sarcoidosis remain unclear (2, 43). Activation of MAPKs is crucial for the synthesis of numerous cytokines and chemokines (23, 44). As we have shown previously, activation of p38 plays a critical role in the regulation of several Th1 cytokines such as IL-12, TNF-α, and IL genes in sarcoidosis (20, 24, 45). In this study, we advance our knowledge by identifying the upstream kinases responsible for p38 activation in sarcoidosis AMs and PBMCs. Activation of several upstream kinases, including MKK3/6, MKK4, and AKT/ASK1, may lead to p38 phosphorylation. Conventional activation of p38 occurs through MKK3/6 activation (46–48). Interestingly, our results demonstrate that p38 activation in sarcoidosis was in parallel with increased MKK4 phosphorylation but not with MKK3/6.

The granulomatous inflammation in sarcoidosis has been linked to TLR2 activation (31). To model the inflammation in sarcoidosis, we challenged AMs and PBMCs obtained from subjects with sarcoidosis with a synthetic TLR2 agonist, PAM, and TLR4 ligand (LPS) and dissected the pathway downstream of TLR2/4. Engagement of TLRs induces MyD88-dependent signaling through the activation of IRAK4, which acts upstream of IRAK1 and phosphorylates this kinase (49). IRAK1 also plays an important role in the inflammasome activation (50). Intriguingly, IRAK1-deficient mice still retain LPS-induced NF-κB activation (51). We have identified that IRAK1, an immune-modulating kinase, is overexpressed in AMs and PBMCs of patients with sarcoidosis compared with healthy control subjects. A small-molecule inhibitor of IRAK1/4, which selectively inhibits its kinase activity in a low micromolar range (IC₅₀ = 0.75 μmol), has been initially developed for autoimmune diseases (52, 53). However, current study indicates that pretreatment of either AMs or PBMCs with IRAK1/4 inhibitor at a pharmacological dose has no significant effect on IL-1β or IL-6 production. Similarly, IRAK1/4 inhibitor did not...
IRAK1 AND Rip2 IN SARCOIDOSIS

IRAK1 and Rip2 inhibitors had a moderate effect on IL-1β and IL-6 production in sarcoidosis AMs. One study found that IRAK1 is constitutively modified, and it regulates IL-10 gene expression in the PBMCs from patients with atherosclerosis (54), suggesting a complex role of IRAK in human disease. IRAK-M is known to play a negative inhibitory role in the TLR pathway (55). We observed higher IRAK-M expression in sarcoidosis PBMCs and AMs as compared with control subjects. Additionally, IRAK1/4 inhibitor pretreatment did not change the expression of IRAK-M in sarcoidosis PBMCs and AMs (data not shown). Interestingly, pretreatment with IRAK1/4 inhibitor in AMs led to an increase Rip2 mRNA. Another study found a differential role of IRAK1/4 kinase activity and function between human versus mouse using the same IRAK1/4 inhibitor in peripheral dendritic cells of patients with systemic lupus erythematosus (37). Our data support these findings of a dichotomy between the role of IRAK1/4 kinase in human PBMCs and AMs as compared with mouse.

The serine/threonine kinase Rip2 mediates signals for receptors of both innate and adaptive immune responses (17, 56). We identified that Rip2 is highly expressed in sarcoidosis AMs and PBMCs. Rip2 has been shown to play an important role in both TLRs and NOD signaling and regulates an optimal TCR signaling (17). However, there is some controversy regarding the role of Rip2 in TLR signaling. Although several studies have shown Rip2 involvement in TLR-mediated MAPKs and NF-κB activation as well as a role in TCR-mediated signaling and T cell differentiation (22, 56), others using knockout mice showed lack of a pivotal role of Rip2 in TLR signaling (57). In contrast to previous studies using knockout mice, we show overexpression and gain of function of Rip2 kinase in sarcoidosis. Activation of p38 by Rip2 is associated with both MKK3/6 and MKK4 MAPK kinases (12). Interestingly, recently, it has been shown that SB203580, which previously was thought to be a specific p38 inhibitor, also inhibits Rip2 kinase (58). Our previous study indicated that SB203580 significantly modulates the inflammatory responses in AMs and PBMCs of patients with sarcoidosis (20). This effect might have been due to Rip2 kinase inhibition beside p38 blockade.

Gefitinib, a EGFR tyrosine kinase inhibitor, has been shown to be a specific inhibitor of Rip2 kinase in macrophages (59). Thus, we determined the effect of dual inhibition of IRAK1/4 and Rip2 on the activation of p38 and inflammatory cytokine production in AMs and PBMCs of patients with sarcoidosis. None of inhibitor was cell toxic as determined by MTT assay. Neither inhibitors targeting IRAK1/4 or Rip2 alone could abrogate IL-1β and IL-6 production in sarcoidosis AMs both at baseline and in response to TLR2 (PAM) or TLR4 ligand (LPS). The combination of IRAK1/4 and Rip2 inhibitors had a moderate effect on IL-1β and IL-6 production in AMs. In contrast to AMs, both the basal as well as PAM-induced IL-1β and IL-6 production in PBMCs of patients with sarcoidosis was significantly inhibited by a combination of IRAK1/4 inhibitor and gefitinib. However, looking at the gene expression, a combination of IRAK1/4 inhibitor and gefitinib inhibited IL-1β mRNA in sarcoidosis AMs and PBMCs. Similar to the decreased cytokine production, a combination of IRAK1/4 inhibitor and gefitinib decreased the activation of p38 in PBMCs as well as a moderate inhibition of p38 phosphorylation in AMs. The synergistic effects of IRAK1/4 and Rip2 inhibitors on cytokine release in PBMCs of patients with sarcoidosis may be due to less sustained activation of p38 MAPK and lower expression of Rip2 kinase as compared with AMs. Further studies need to determine whether the inhibitory effect of gefitinib on cytokine production is solely due to Rip2 or additional EGFR inhibition. We observed that AMs compared with PBMCs of the same patient exhibit higher cytokine production and higher phospho-p38 activity. This could be due to the fact that tissue-resident macrophages exhibit a more inflammatory phenotype, or it may be due to a mixed population in PBMCs.

p38α MAPK is the major isoform in T cells and is involved in signaling of IFN-γ production by Th1 cells (44). Studies have demonstrated that the p38 pathway is involved in the production of IFN-γ by CD4 and CD8 T cells (60). Although MKK3, MKK4, and MKK6 MAPK kinases can activate p38 in T cells, it has been shown that there is a stimuli-dependent preferential activation of these kinases (61). In sarcoidosis, lymphocytes (T and B cells) and AMs play a role in the disease process. In T cells, p38 phosphorylation occurs through a noncanonical alternative pathway, Lck-ZAP70–mediated phosphorylation at Tyr323 (62). Tyr323 phosphorylation has been shown to be the major mechanism of TCR-induced p38 activation and IFN-γ production by T cells. In the current study, we did not detect significant p38 Tyr323 activation in BALs or PBMCs of patients with sarcoidosis (data not shown).

In our study, the sarcoidosis PBMCs responded to anti-CD3 stimulation with increased IL-6 and IFN-γ production. Similar to TLR2- and TLR4-mediated IL-1β induction in sarcoidosis AMs and PBMCs, because pharmacological inhibition of IRAK1/4 not only did not reduce IL-1β and IL-6 but increased IL-1β mRNA and IL-6 production in sarcoidosis AMs. One study found that IRAK1 is constitutively modified, and it regulates IL-10 gene expression in the PBMCs from patients with atherosclerosis (54), suggesting a complex role of IRAK in human disease. IRAK-M is known to play a negative inhibitory role in the TLR pathway (55). We observed higher IRAK-M expression in sarcoidosis PBMCs and AMs as compared with control subjects. Additionally, IRAK1/4 inhibitor pretreatment did not change the expression of IRAK-M in sarcoidosis PBMCs and AMs (data not shown). Interestingly, pretreatment with IRAK1/4 inhibitor in AMs led to an increase Rip2 mRNA. Another study found a differential role of IRAK1/4 kinase activity and function between human versus mouse using the same IRAK1/4 inhibitor in peripheral dendritic cells of patients with systemic lupus erythematosus (37). Our data support these findings of a dichotomy between the role of IRAK1/4 kinase in human PBMCs and AMs as compared with mouse.

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mechanistic pathway that could be valuable for the development of new therapeutic targets for sarcoidosis.

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Disclosures
The authors have no financial conflicts of interest.

References


