Toll-like Receptor 2 and Mitogen- and Stress-activated Kinase 1 Are Effectors of Mycobacterium avium-induced Cyclooxygenase-2 Expression in Macrophages*

Received for publication, August 27, 2004, and in revised form, October 12, 2004

Sushil Kumar Pathak‡, Asima Bhattacharyya, Shresh Pathak, Chaitali Basak, Debrabrata Mandal, Manikuntala Kundu‡, and Joyoti Basu‡

From the Department of Chemistry, Bose Institute, 93/I Acharya Prafulla Chandra Road, Calcutta 700009, India

Understanding how pathogenic mycobacteria subvert the protective immune response is crucial to the development of strategies aimed at controlling mycobacterial infections. Prostaglandin E₂ exerts an immunosuppressive function in the context of mycobacterial infection. Because cyclooxygenase-2 (COX-2) is a rate-limiting enzyme in prostaglandin biosynthesis, there is a need to delineate the mechanisms through which pathogenic mycobacteria regulate COX-2 expression in macrophages. Our studies demonstrate that the NF-κB and CRE elements of the COX-2 promoter are critical to Mycobacterium avium-induced COX-2 gene expression. M. avium-triggered signaling originates at the Toll-like receptor 2 (TLR2). Ras associates with TLR2 and activates the mitogen-activated protein kinase (MAPK) extracellular signal-regulated kinase (ERK), whereas tumor necrosis factor receptor-associated factor 6 (TRAF6)/transforming growth factor β-activated kinase 1 (TAK1)-dependent signaling activates p38 MAPK. Both ERK and p38 MAPK activation converge to regulate the activation of mitogen- and stress-activated kinase 1 (MSK1). MSK1 mediates the phosphorylation of the transcription factor CREB accounting for its stimulatory effect on CRE-dependent gene expression. M. avium-triggered cytoplasmic NF-κB activation following IκB phosphorylation is necessary but not sufficient for COX-2 promoter-driven gene expression. MSK1 activation is also essential for M. avium-triggered NF-κB-dependent gene expression, presumably mediating nucleosomal modifications. These studies demonstrate that the nuclear kinase MSK1 is necessary in regulating the pathogen-driven expression of a gene by controlling two transcription factors. The attenuation of MSK1 may therefore have potential benefit in restricting survival of pathogenic mycobacteria in macrophages.

To design novel therapeutics and to rationalize vaccination strategies against mycobacterial diseases, it is of foremost importance to understand the mechanisms by which mycobacteria subvert the protective immune response. The response of macrophages to invasion by intracellular pathogens such as mycobacteria depends on the signals triggered during the initial contact of the bacterium with the macrophages. Prostaglandin E₂ (PGE₂) is believed to exert an immunosuppressive function in the context of mycobacterial infections. PGE₂ interferes with T lymphocyte responses by inhibiting the production of interleukin-2 (1). PGE₂ also inhibits the secretion of interferon-γ, which is important in activating T cells and macrophages (2). Cooper and colleagues (3) reported that the ability of the virulent Mycobacterium avium to attenuate macrophage activation was dependent on its ability to trigger p38 mitogen-activated protein kinase (MAPK)-dependent production of PGE₂. These observations were supported by a case report in which monocytes from a child with disseminated M. avium infection demonstrated a defect in bactericidal activity which could be offset by treatment with indomethacin (4). The critical role of PGE₂ is also supported by a report that human immunodeficiency virus envelope glycoprotein (gp120) can enhance M. avium replication within macrophages by induction of PGE₂ (5).

Cyclooxygenase-2 (COX-2) is a key enzyme catalyzing the rate-limiting step in the inducible production of prostaglandins. COX-2 catalyzes the conversion of arachidonic acid to PGH₂, which is then metabolized by terminal synthases to a variety of biologically active prostanoids (6). COX-2 gene expression is regulated at the level of transcription as well as post-transcriptionally. The regulation of the COX-2 promoter in macrophages is complex and involves different promoter elements. The transcriptional activation of the COX-2 gene depends on the stimulus-coupled binding of transcription factors (7), including NF-κB, C/EBPβ, and AP-1 (8–12). The CRE-element is the most generally required promoter element, being essential for both basal and induced COX-2 transcription in a variety of cell types (13–17). The specific factors regulating COX-2 induction depend on the cell type as well as on the stimulus.

Considering that COX-2 is likely to play a critical role in M. avium-triggered PGE₂ release from macrophages, we set out to explore the signaling cascades and the cis-regulatory elements governing COX-2 induction from M. avium-challenged macrophages. Our results demonstrate that TLR2-dependent ERK and p38 activation converge upon the activation of mitogen- and stress-activated kinase 1 (MSK1), which is

* This work was supported in part by grants from the National Bioscience Award for Career Development of the Department of Biotechnology, Government of India, the Department of Atomic Energy, Government of India, and the Department of Science and Technology, Government of India, and the Department of Science and Technology, Government of India, the Department of Bio-immunodeficiency virus envelope glycoprotein (gp120) can enhance M. avium replication within macrophages by induction of PGE₂ (5).

† Supported by a Junior Research Fellowship from the Council of Scientific and Industrial Research, Government of India.
‡ To whom correspondence may be addressed. Tel.: 91-33-2350-6619; Fax: 91-33-2350-6790; E-mail: joyoti@vsnl.com (J. B.) or manikuntala@vsnl.net (M. K.).

§ The abbreviations used are: PGE₂, prostaglandin E₂; COX-2, cyclooxygenase-2; ERK, extracellular signal-regulated kinase; MAPK, mitogen-activated protein kinase; TLR2, Toll-like receptor 2; MSK1, mitogen- and stress-activated kinase 1; PBS, phosphate-buffered saline; m.o.i., multiplicity of infection; CMV, cytomegalovirus; TBS, Tris-buffered saline; GST, glutathione S-transferase; LPS, lipopolysaccharide.

This paper is available on line at http://www.jbc.org
instrumental in controlling both NF-κB and CRE-driven transcrip
tion of the COX-2 gene. To NF-kB and CRE-driven tran-
scription of the COX-2 gene. To the best of our knowledge, this
is the first demonstration of the role of MSK1 in controlling
pathogen-driven gene expression of COX-2, a molecule that
plays a central role in pathogenesis.

**EXPERIMENTAL PROCEDURES**

U0126, SB203580, H89, and manucycin A were purchased from
EMD Biosciences, San Diego, CA. Polyomycin B, CREBTDIE, anti-
CREB and anti-FLAG-agarose were products of Sigma. Protease inhib-
itors were from Roche Applied Science. Antibodies to MSK1, p65, and
p50 were purchased from Santa Cruz Biotechnology Inc. (Santa Cruz,
CA). Antibodies specific for p38 MAPK, ERK, phospho-ERK, phospho-
p38, phospho-CREB, and anti-Ras were from Cell Signaling Technology
(Beverly, MA). Anti-TLR2 antibody was from Imgenex India (Bhu-
raneswar). [γ-32P]ATP was from Jonaki, BRIT (Hyderabad, India).

**Growth of M. avium**—M. avium (NCTC 8562) was obtained from the
All India Institute of Medical Sciences, New Delhi), grown in Middle-
broth 7H9 broth (Difco, Detroit, MI) supplemented with oleic acid-
albumin-dextrose supplement and 0.04% Tween 80 until mid-log phase,
harvested, and resuspended in a small volume of phosphate-
buffered saline (PBS) containing 0.04% (v/v) Tween 80. The suspension
was briefly sonicated until no bacterial clumps were visualized by
microscopy. The preparation was diluted to a concentration of 2 x 10^6
colonies per ml in 10% glycerol and stored in aliquots at
-80 °C. Freshly thawed aliquots were used no more than once. Where
indicated, cells were incubated with polyoxymycin B (10 µg/ml) for 30 min
prior to use.

**Cell culture**—The murine macrophage cell line RAW264.7 was
obtained from the National Centre for Cell Science, Pune, India, and
cultured in Dulbecco’s modified Eagle’s medium supplemented with
10% fetal bovine serum, 2 mM glutamine, and antibiotics. Where
indicated, RAW264.7 cells were challenged with M. avium at a multiplicity of infection (m.o.i.) of 2.

**Plasmid constructs**—Using genomic DNA from RAW264.7 cells as
a template, the COX-2 promoter region (−891 to +0) was amplified by
PCR using the primer pair 5'-CCGATTCTACCAAACTGTCTTTCT-
GA-3' (sense) and 5'-TCGGTACCTGAAAGCTGCTTGC-3' (antisense)
and 5'-CCGAGATCCAGCTAATGCT-3' (antisense primer b). The result-
ing COX-2 promoter region was cloned into the vector pGL2 Basic (Promega) harboring the pro-

tomer-less luciferase gene, using asymmetric KpnI and Hind III sites (underlined)

to generate the plasmid pCOX301. NF-κB (−402/−392, 30), C/EBPβ (−135/−130), AP-1 (−65/−60), and CRE (−60/−56) binding sites

were mutated by deleting the underlined bases from the respective sites

indicated: 5'-GGGATCCCT-3' (for NF-κB), 5'-TCCAGGTCA-3' (for C/EBPβ), 5'-AACAGATCCACA-3' (for AP1) and 5'-CAGTACGGTA-3' (for CRE).

Mutants were generated by overlap extension PCR. The primers

used are depicted in Table I. The initial rounds of PCR were carried out

using the primer pairs a and b for one reaction, c and d for the second

reaction, and pCOX301 as template. The products of each PCR

were purified and used as templates for the second round of PCR using

the primers a and d. The final products were cloned between the Kpn1 and

HindIII sites of pGL2 Basic. Vectors for wild type and dominant-

negative Ras (Ras S17N); wild type and dominant-negative (S32A, S36A)

IκBα in pCMV were purchased from BD Biosciences. For generating

FLAG-tagged Ras expression vectors, the respective genes were excised

from the parent vectors described above using EcoRI and BamHI and

cloned between the EcoRI and BamHI sites in pFLAG-CMV6c. Wild
type and dominant-negative (K63W) HA-TAK1 were gifts from Dr. Kuni Matsumoto, Nagoya

University, Japan; wild type and dominant-negative (D195A) MSK1 in

pCMV-FLAG were gifts from Dr. Dario Alessi, University of Dundee,

UK. Wild type TLR4 (sTLR4) in pEF-Bos was a gift from Dr. Yoshinori

Nagai of the University of Tokyo, Japan. Dominant-negative sTLR4

(PT127H) was generated by site-directed mutagenesis based on the prin-

ciple of overlap extension PCR. Using pEF-BOS-TLR4 as template,

the first round of PCR was performed with primer pairs a and b for one

reaction and primer pairs c and d for the second reaction. The second

round of PCR was performed using the products of the first round as

templates, and primers a and d. Primers a, b, c, and d were 5'-ACAG-

AATCTCAGCGTTCTTACTAACC-3' (sense) and 5'-CATCCTAGTGTGACTGTA-

GCC-3', 5'-GCTGCACTACGTAATAGTTC-3', and 5'-CGCCGATGCT-

GGTCAATTGGGCTCTTC-3', respectively. The resulting 1.2-kb PCR

product was cloned in pUC19 between the EcoRI and BamHI sites,

sequenced on both strands, and an Xho-BamHI (488 bp) fragment

containing the mutated TLR4 gene encoding amino acid residues 679–

835 was then excised and used to replace the Xho-BamHI fragment of

wild type TLR4 in pEF-BOS. pNF-κB-luc containing four NF-κB sites in

tandem fused to the luciferase reporter gene, was a gift from Dr. A.

Brent Carter of the University of Iowa. The p6CRE-luc construct con-

taining 6 CRE sites in tandem fused to the luciferase reporter gene was

a gift from Dr. Steve Rees of GlaxoSmithKline. pOEX/Raf-BBD was a

gift from Dr. Robert J. Sheaff of the University of Minnesota. cDNA

products for murine TLR2 and CREB were obtained by reverse

transcription-PCR from a total RNA preparation from RAW264.7 cells using

the primers: 5'-CTATCGTCTATGATGTCCTATC-3' (sense) and 5'-GCCGCTCGAGGCTGACTATTGC-3' (antisense) for TLR2; and 5'-ATAAAGCTTATGAGAATCTTGA-3' (sense) and 5'-AGATTCATTTGTTGGAAGTTTAC-3' (antisense) for CREB. The PCR products were cloned into pDNA3.1 (between Nhel and XhoI sites) for TL2R2 and pFLAG-CMV-6a (between HindIII and BamHI sites) for CREB. For generating dominant-negative dominant TLR2 (carrying a 13-amino acid deletion from the C terminus), a 2313-bp fragment was amplified by PCR using the sense primer mentioned above and the antisense primer: 5'-CCGCTCGAGGCTGCTTAGTTGA-3' (sense) and 5'-ATCGGTCGAGCGGTGCCTAGTTGA-3' (antisense) for CREB. The PCR products were cloned into pDNA3.1 (between Nhel and XhoI sites) for TL2R2 and pFLAG-CMV-6a (between HindIII and BamHI sites) for CREB. For generating dominant-negative dominant TLR2 (carrying a 13-amino acid deletion from the C terminus), a 2313-bp fragment was amplified by PCR using the sense primer mentioned above and the antisense primer: 5'-CCGCTCGAGGCTGCTTAGTTGA-3' (sense) and 5'-ATCGGTCGAGCGGTGCCTAGTTGA-3' (antisense) for CREB. The PCR products were cloned into pDNA3.1 (between Nhel and XhoI sites) for TL2R2 and pFLAG-CMV-6a (between HindIII and BamHI sites) for CREB. For generating dominant-negative dominant TLR2 (carrying a 13-amino acid deletion from the C terminus), a 2313-bp fragment was amplified by PCR using the sense primer mentioned above and the antisense primer: 5'-CCGCTCGAGGCTGCTTAGTTGA-3' (sense) and 5'-ATCGGTCGAGCGGTGCCTAGTTGA-3' (antisense) for CREB. The PCR products were cloned into pDNA3.1 (between Nhel and XhoI sites) for TL2R2 and pFLAG-CMV-6a (between HindIII and BamHI sites) for CREB.
Mycobacteria-induced COX-2 Expression in Macrophages

Electrophoretic Mobility Shift Assay—To prepare nuclear extracts, plates with adhered cells were washed twice with ice-cold PBS and scraped in ice-cold TNE buffer (40 mM Tris HCl, pH 7.5, 0.1 M NaCl, 1 mM EDTA). Cells were pelleted at 600 × g for 1 min, and pellets were resuspended in 400 μl of lysis buffer (10 mM HEPES, pH 7.9, 10 mM KCl, 0.1 mM EDTA, 1 mM EGTA, 1 mM dithiothreitol, 0.5 mM Pefabloc, 2 μg/ml leupeptin, 2 μg/ml aprotinin, 0.5 mg/ml benzamidine). Cells were lysed by the addition of 25 μl of 10% (v/v) Nonidet P-40 (Nonidet M) or U0126 (15 μM) or a combination of U0126 and SB203580 at the same concentrations, or H89 (10 μM) for 30 min followed by the treatment with M. avium at an m.o.i. of 2 for 8 h. The expression of COX-2 in the lysates was analyzed by Western blotting using anti-COX-2 antibody. The blot is representative of the results obtained in three independent experiments.

**FIG. 1.** M. avium stimulates PGE2 release and COX-2 expression in RAW264. 7 cells. **A** and **B**. RAW264.7 cells were transfected with empty vector (pcDNA3.1 or pEF-BOS) or with dominant-negative(Δ)TLR4 (TLR4Δ712H) or -TLR2, followed by treatment with M. avium at an m.o.i. of 2 for 8 h. PGE2 release was subsequently assayed. Results shown represent the means ± S.D. of three independent experiments. C, 5 × 10⁵ cells were seeded in a 24-well plate, treated with M. avium at an m.o.i. of 2 for different periods of time periods as indicated, washed, and lysed. The expression of COX-2 was determined by centrifugation at 10,000 g for 1 min, and pellets were washed, and lysed. The expression of COX-2 in the lysates was analyzed by Western blotting using anti-COX-2 antibody. The blot is representative of the results obtained in three independent experiments.

**D**. Cells were left untreated or treated with U0126 (15 μM) or SB203580 (5 μM) or manucycin A (10 μM) or a combination of U0126 and SB203580 at the same concentrations, or H89 (10 μM) for 30 min followed by the treatment with M. avium at an m.o.i. of 2 for 8 h. Expression of COX-2 was analyzed as described in panel C. The blot is representative of results obtained in three independent experiments; panel E represents the results obtained from densitometric scanning of these gels (means ± S.D.). E, cells were left untreated or pretreated with the inhibitors SB203580 (5 μM) or U0126 (15 μM) or a combination of U0126 and SB203580 at the same concentrations, or H89 (10 μM) for 30 min followed by the treatment with M. avium at an m.o.i. of 2 for 6 h. Total RNA was isolated and reverse transcription-PCR was performed using primers specific for the COX-2 or glyceraldehyde-3-phosphate dehydrogenase (gpdh) genes. The products were visualized on agarose gels by ethidium bromide staining. The data shown are representative of results obtained from three independent experiments.

**F.** Luciferase reporter assays—Cells were transfected with luciferase reporter plasmid. Transfected cells were challenged with M. avium, washed once with PBS, and scraped into luciferase lysis buffer (50 mM Tris, pH 8, 70 mM K₂HPO₄, 0.1% Nonidet P-40, 2 mM MgCl₂, 1 mM dithiothreitol, 20 μg/ml aprotinin, 10 μg/ml pepstatin, 0.5 mg/ml benzamidine). The lysates were rapidly mixed, and insoluble material was pelleted by centrifugation at 4 °C. The supernatant was removed and stored at −80 °C. For promoter activation analysis, luciferase activity containing the COX-2 gene-specific NF-κB binding site (5′-GGT-GAGGGGAGTCTCCCTTAGTTA-3′) (or the mutated oligonucleotide with the sites of mutation (GA → CC) in boldface) or the COX-2-specific CRE site (5′-GTACCACACGTCACGTTGAG-3′) (or the mutated oligonucleotide with the sites of mutation (AGC → GAT) in boldface) was added, and the mixture was incubated for 30 min at 25 °C. The DNA-protein complex formed was separated from the oligonucleotide on a 4% native polyacrylamide gel. The gel was dried and analyzed by autoradiography. For supershift assays, nuclear extracts were incubated for 30 min at 25 °C with rabbit polyclonal antibodies against p50, p65 (for NF-κB), or CREB (for CRE) or no antibody before incubation with the radiolabeled probe.
were immunoprecipitated with anti-FLAG agarose and then immunoblotted with anti-FLAG antibody. The results are representative of results obtained in three independent experiments.

**Ras Activity Assay**—Ras activity was measured by assaying for Ras proteins bound to the Ras-binding domain of Raf-1 expressed as a GST fusion protein (18). Briefly, cells (2 × 10^6) after treatment were washed with ice-cold PBS, lysed in lysis buffer (25 mM HEPES, pH 7.5, 150 mM NaCl, 10 mM MgCl_2, 5 mM EDTA, 25 mM NaF, 1 mM sodium orthovanadate, 10% glycerol, 10 μg/ml aprotinin, and 10 μg/ml leupeptin) and centrifuged. Lysate was incubated with 5 μg of Ras-binding domain of Raf-1 (Raf-1 RBD) at 4 °C for 3 h with gentle agitation, and the beads were washed thrice in lysis buffer. Bound Ras proteins were solubilized in Laemmli buffer and detected by SDS-PAGE followed by Western blotting using anti-Ras antibody.

**Co-immunoprecipitation of Ras with TLR2**—RAW 264.7 cells were transfected with FLAG-Ras expressing vector and challenged with M. avium for the indicated time periods. The cells were harvested, lysed in lysis buffer (40 mM Tris-HCl (pH 8.0), 500 mM NaCl, 0.1% Nonidet P-40, 6 mM EGTA, 10 mM sodium β-glycerophosphate, 10 mM NaF, 300 μM sodium orthovanadate, 2 mM phenylmethylsulfonyl fluoride, 10 μg/ml aprotinin, 1 μg/ml leupeptin, and 1 mM dithiothreitol), and centrifuged. The supernatant was then immunoprecipitated with anti-FLAG-agarose. The immunoprecipitated beads were washed three times with lysis buffer. The samples were fractionated on 15% SDS-polyacrylamide gels, transferred to a polyvinylidene difluoride membrane, and subjected to immunoblot analysis with antibodies specific for TLR2.

**MSK1 Assay**—Cells were washed with ice-cold PBS and lysed in lysis buffer containing 50 mM Tris-HCl, pH 7.5, 1 mM EDTA, 1 mM EGTA, 1 mM sodium orthovanadate, 1% (v/v) Triton X-100, 50 mM NaF, 5 mM sodium pyrophosphate, 0.27 M sucrose, 0.1% (v/v) β-mercaptoethanol, 1 mM benzamidine, 2 μg/ml leupeptin, and 0.2 mM Pefabloc. Lysates were clarified by centrifugation (5 min, 10,000 × g, 4 °C). MSK1 was immunoprecipitated by incubation with anti-MSK1 antibody. The immunoprecipitates were washed three times with lysis buffer and twice with kinase buffer (50 mM Tris-HCl, pH 7.4, 10 mM MgCl_2, 0.1 mM EGTA, 10 mM NaF, and 0.1% (v/v) β-mercaptoethanol). Beads were resuspended in 50 μl of kinase buffer containing 30 μM substrate peptide: ELISPRPSYRK (CREB-TIDE) and 0.1 mM [γ-32P]ATP (20,000,000 cpm/μl). After incubation at 30 °C for 30 min, the incorporation of phosphates in CREB-TIDE was determined using p81 phosphocellulose paper (19).

**RESULTS**

**M. avium Stimulates PGE_2 Release from RAW264.7 Macrophages**—Considering that PGE_2 release is one of the mechanisms used by virulent M. avium to down-regulate macrophage activation (3), we sought to investigate the mechanisms of M. avium-stimulated PGE_2 release from RAW264.7 macrophages. The levels of PGE_2 released from RAW264.7 cells were measured using an enzyme-linked immunosorbent assay. Challenge of macrophages with M. avium for 8 h induced a rise in PGE_2 levels (Fig. 1A). Members of the TLR protein family are key regulators of innate immune activation induced by pathogenic mycobacteria (20). M. avium signals in macrophages through TLR2 (21). Consistent with a role of TLR2-dependent signaling in M. avium-stimulated PGE_2 release, transfection of RAW264.7 cells with dominant-negative TLR2, led to abrogation of PGE_2 release following M. avium challenge (Fig. 1B). On the other hand, cells transfected with dominant-negative TLR4 (TLR4 harboring the mutation P712H) still showed release of PGE_2 when challenged with M. avium. In results described in Fig. 5, we have validated that TLR4(P712H) does function as a dominant-negative in the present context. TLR4 therefore did not appear to play any role in M. avium-mediated PGE_2 release.

**M. avium-stimulated PGE_2 Release Depends on the ERK and p38 MAPKs**—PGE_2 release from M. avium-challenged cells was inhibited when cells were pretreated with pharmacological inhibitors of ERK and p38 MAPKs, U0126 and SB203580, respectively (Fig. 1A). Although other effectors such as bacterial peptidoglycan have been reported to modulate PGE_2 release by activating COX-2 expression in a phosphatidylinositol 3-kinase-dependent manner, the phosphatidylinositol 3-kinase inhibitor wortmannin had no effect on PGE_2 release in the present instance. The ERK and p38 MAPKs appeared to regu-
late PGE2 release in a synergistic manner, because a combination of the inhibitors U0126 and SB203580 led to a complete inhibition of PGE2 release (Fig. 1A). Besides their ability to phosphorylate and activate transcription factors, both ERK and p38 MAPK also transduce signals by activating downstream kinases such as mitogen- and stress-activated protein kinase 1 (MSK1), which in turn phosphorylates transcription factors. Cells pretreated with H89, a pharmacological inhibitor of MSK1, at the dose used led to a complete inhibition of PGE2 release (Fig. 1A), suggesting a role of MSK1 in PGE2 release.

M. avium Stimulates COX-2 Expression—COX-2 converts arachidonic acid released from the cell lipids by the action of phospholipase A2 to prostaglandin H2, the common precursor of all prostaglandins. To examine whether elevated PGE2 synthesis is associated with increased COX-2 expression we studied the M. avium-induced expression of COX-2. Western analysis showed that M. avium challenge resulted in a time-dependent increase in the expression of COX-2 in RAW264.7 (Fig. 1C). COX-2 expression is regulated by, among others, transcriptional mechanisms (7–12). We therefore analyzed the expression of the COX-2 gene in M. avium-challenged macrophages by reverse transcription-PCR. Compared with untreated cells, the steady-state COX-2 mRNA levels increased in cells treated with M. avium (Fig. 1E). Taken together, our results on activation of COX-2 at the level of the gene and the protein in cells challenged with M. avium suggested that this regulation is likely to be critical in controlling PGE2 release from these cells.

M. avium-induced COX-2 Expression Is Dependent on the MAPKs—Considering the role of MAPK inhibitors in inhibiting PGE2 release, we tested the role of MAPKs in M. avium-induced COX-2 expression. As shown in Fig. 1 (D and F), M. avium-induced COX-2 expression could be attenuated partially either by U0126 or by SB203580 alone, suggesting a role of ERK as well as p38 MAPKs in M. avium-triggered COX-2 expression. As in the case of PGE2 release, COX-2 expression was completely inhibited either by a combination of U0126 and SB203580, or by H89. The levels of COX-2 mRNA were also similarly regulated (Fig. 1E). These results suggested the possibility that COX-2 gene expression is coordinately regulated by ERK and p38 MAPKs regulating MSK1. This possibility has been tested in the following sections.

Ras Is Involved in M. avium-induced COX-2 Expression—The small GTP-binding protein Ras is an important signal mediator in response to stimuli such as growth factors, cytokines, and hormones (22). In resting cells, Ras is maintained in...
an inactivated Ras-GDP form. After activation, Ras is converted into active Ras-GTP. Ras exerts its function through activating downstream effectors, among which the best studied is the MAPK cascade (23). Considering the role of ERK and p38 MAPKs in regulating PGE2 release as well as COX-2 expression in response to *M. avium* challenge, we tested the effect of the Ras inhibitor manumycin A (24) on *M. avium*-induced COX-2 expression. Cells were pretreated with manumycin A prior to challenge with *M. avium*. Manumycin A partially inhibited *M. avium*-induced COX-2 expression (Fig. 1, D and F). To further confirm the role of Ras in *M. avium*-induced signaling in RAW264.7 cells, the activation of Ras was assessed by an activation assay relying on the interaction of activated Ras with Raf-1-RBD (18). Upon *M. avium* challenge, Ras activity increased in a time-dependent manner (Fig. 2, A and B). Taken together, these results suggested that *M. avium*-induced COX-2 expression depends on Ras activation.

**TLR2 Associates with Ras in *M. avium*-stimulated Macrophages**—Because *M. avium*-mediated PGE2 release is inhibited by dominant-negative TLR2, we tested the hypothesis that rapid Ras activation could be linked to TLR2 signaling. It was observed that *M. avium*-induced Ras activation was blocked in cells transfected with dominant-negative TLR2 (Fig. 2, C and D). To test whether rapid Ras activation is concurrent with Ras-TLR2 interaction, RAW264.7 cells were transfected with FLAG-tagged Ras and challenged with *M. avium*, and lysates were prepared and immunoprecipitated with anti-FLAG antibody and immunoblotted for the presence of TLR2 in the immunoprecipitated complex. The association of Ras and TLR2 occurred in a time-dependent manner (Fig. 2E). The immunoprecipitate showed no band corresponding to TLR2 when it was blotted with an irrelevant antibody. Control experiments were performed in which an irrelevant FLAG-tagged protein was transfected prior to challenge with *M. avium*. Co-immunoprecipitation of TLR2 with anti-FLAG antibody was not visible in this case. Taken together, all these results suggested that *M. avium*-induced Ras activation occurs through interaction of Ras with TLR2.

**M. avium-induced ERK Activation Depends on TLR2/Ras Signaling**—Our previous studies have already demonstrated that *M. avium* activates ERK and p38 MAPKs in macrophages (25). In the present study we observed that pretreatment with manumycin A (Fig. 3, A and B) inhibited the phosphorylation of ERK in a dose-dependent manner. This suggested that ERK was downstream of Ras signaling. Further, transfection of cells with dominant-negative TLR2 or dominant-negative Ras led to an inhibition of *M. avium*-induced ERK phosphorylation (Fig. 3C), supporting the view that *M. avium* activates ERK in a TLR2/Ras-dependent signaling pathway.

**M. avium-induced p38 MAPK Activation Depends on TLR2/TRAF6 Signaling**—*M. avium*-induced p38 MAPK activation was inhibited by transfecting cells with dominant-negative constructs of TLR2, TRAF6, or TAK1 (Fig. 3D). TAK1 is known to signal downstream of the TLRs to activate p38 MAPK in response to a variety of stimuli (26, 27). Because TLR2/TRAF6/TAK1 signaling is a well established pathway of MAPK activation, we felt it safe to predict that this pathway controls the activation of p38 MAPK in the present instance also.

**M. avium Stimulates COX-2 Promoter Activity**—COX-2 expression is controlled by both transcriptional and post-transcriptional mechanisms. To determine whether *M. avium* regulates COX-2 promoter activity, RAW 264.7 cells were transfected with different constructs of the mouse COX-2 promoter coupled with the luciferase reporter gene. *M. avium* evoked at least a 10-fold increase in luciferase activity in cells transiently expressing COX-2 promoter (−891 to +9)-luc transfection construct or mutant constructs along with *B. subtilis* reporter construct or mutant constructs.

**Results**

Luciferase reporter activities were measured in cell extracts using luciferin as a substrate. The level of induction of luciferase activity was compared with that of untreated cells. The level of induction of luciferase activity was compared with that of untreated cells. Data were normalized with respect to β-galactosidase activity. Results represent means ± S.D. of three independent experiments. B and C, electrophoretic mobility shift assays. RAW264.7 cells were left untreated or challenged with *M. avium* for 3.5 h. The nuclear extracts were subjected to EMSA using labeled COX-2-specific NF-κB (B) or CRE (C) DNA probes. Where required, the binding reaction was performed in the presence of competitor (unlabeled) oligonucleotides or supershift antibodies as indicated. The arrowheads indicate the positions of bands. Gels are representative of results obtained from three independent experiments.

**Discussion**

**Ras and COX-2 Expression**

Our previous studies have already demonstrated that Ras is involved in the regulation of COX-2 expression (28). Because Ras is known to activate downstream effectors, among which the best studied is the MAPK cascade (23), we investigated the role of Ras in COX-2 expression. In RAW264.7 cells, the activation of Ras was assessed by an activation assay relying on the interaction of activated Ras with Raf-1-RBD (18). Upon *M. avium* challenge, Ras activity increased in a time-dependent manner (Fig. 2, A and B). Taken together, these results suggested that *M. avium*-induced COX-2 expression depends on Ras activation.

**TAK1 Signaling**

TAK1 is known to play a crucial role in the activation of MAPKs in response to a variety of stimuli (26, 27). Because TLR2/TRAF6/TAK1 signaling is a well established pathway of MAPK activation, we felt it safe to predict that this pathway controls the activation of p38 MAPK in the present instance also.

**TLR2 Associates with Ras in *M. avium*-stimulated Macrophages**—Because *M. avium*-mediated PGE2 release is inhibited by dominant-negative TLR2, we tested the hypothesis that rapid Ras activation could be linked to TLR2 signaling. It was observed that *M. avium*-induced Ras activation was blocked in cells transfected with dominant-negative TLR2 (Fig. 2, C and D). To test whether rapid Ras activation is concurrent with Ras-TLR2 interaction, RAW264.7 cells were transfected with FLAG-tagged Ras and challenged with *M. avium*, and lysates were prepared and immunoprecipitated with anti-FLAG antibody and immunoblotted for the presence of TLR2 in the immunoprecipitated complex. The association of Ras and TLR2 occurred in a time-dependent manner (Fig. 2E). The immunoprecipitate showed no band corresponding to TLR2 when it was blotted with an irrelevant antibody. Control experiments were performed in which an irrelevant FLAG-tagged protein was transfected prior to challenge with *M. avium*. Co-immunoprecipitation of TLR2 with anti-FLAG antibody was not visible in this case. Taken together, all these results suggested that *M. avium*-induced Ras activation occurs through interaction of Ras with TLR2.

**M. avium-induced ERK Activation Depends on TLR2/Ras Signaling**—Our previous studies have already demonstrated that *M. avium* activates ERK and p38 MAPKs in macrophages (25). In the present study we observed that pretreatment with manumycin A (Fig. 3, A and B) inhibited the phosphorylation of ERK in a dose-dependent manner. This suggested that ERK was downstream of Ras signaling. Further, transfection of cells with dominant-negative TLR2 or dominant-negative Ras led to an inhibition of *M. avium*-induced ERK phosphorylation (Fig. 3C), supporting the view that *M. avium* activates ERK in a TLR2/Ras-dependent signaling pathway.

**M. avium-induced p38 MAPK Activation Depends on TLR2/TRAF6 Signaling**—*M. avium*-induced p38 MAPK activation was inhibited by transfecting cells with dominant-negative constructs of TLR2, TRAF6, or TAK1 (Fig. 3D). TAK1 is known to signal downstream of the TLRs to activate p38 MAPK in response to a variety of stimuli (26, 27). Because TLR2/TRAF6/TAK1 signaling is a well established pathway of MAPK activation, we felt it safe to predict that this pathway controls the activation of p38 MAPK in the present instance also.

**M. avium Stimulates COX-2 Promoter Activity**—COX-2 expression is controlled by both transcriptional and post-transcriptional mechanisms. To determine whether *M. avium* regulates COX-2 promoter activity, RAW 264.7 cells were transfected with different constructs of the mouse COX-2 promoter coupled with the luciferase reporter gene. *M. avium* evoked at least a 10-fold increase in luciferase activity in cells transiently expressing COX-2 promoter (−891 to +9)-luc transfection construct or mutant constructs.
pared with untreated cultures (Fig. 4A). To rule out the effect of contaminating lipopolysaccharide (LPS) on COX-2 promoter-activated gene expression, *M. avium* cells were first incubated with polymyxin B before challenge of macrophages. The expression of luciferase was unchanged using polymyxin B-treated as compared with untreated *M. avium* (Fig. 5A).

The NF-κB and CRE Sites Are Essential for Optimal COX-2 Promoter-induced Reporter Induction in *M. avium*-stimulated Macrophages—In macrophages, several cis-acting elements have been found to play a role in COX-2 gene transcription (7–12). To assess the role of the potential cis-acting elements in *M. avium*-induced COX-2 gene transcription, the NF-κB, CRE, C/EBPβ, and AP-1 elements were individually mutated (as depicted in Fig. 4A) to evaluate the effects of such mutations on *M. avium*-stimulated COX-2 promoter activity. The COX-2 reporter constructs were transiently transfected into RAW264.7 macrophages. Cells were subsequently challenged with *M. avium* for 6 h, harvested, and lysed for luciferase activity reporter activity induced by *M. avium*. Our results demonstrate that the constructs mutated at the AP-1 and C/EBPβ sites were as effective in stimulating luciferase gene expression as the wild-type COX-2 promoter (Fig. 4A). However, there was partial inhibition of luciferase gene expression when either the NF-κB or the CRE site was mutated, suggesting that *M. avium*-induced COX-2 promoter activation depends on the NF-κB as well as the CRE elements. Luciferase expression was completely inhibited when both the NF-κB and the CRE sites were mutated (Fig. 4A).

**IkB-α Phosphorylation Is Necessary for *M. avium*-driven COX-2 Promoter Activation**—In most cell types, NF-κB is maintained in an inactive form in the cytoplasm by association with IkB-α. In the better known mechanisms of NF-κB activation, TLR signaling leads to the IkB-α kinase-dependent phosphorylation of IkB-α, its ubiquitination and degradation by the proteasome, accompanied by the release and subsequent translocation of NF-κB into the nucleus (28). The likely involvement of this classic pathway in *M. avium*-induced COX-2 promoter activation was tested. Transfection with dominant-negative TLR2 led to an inhibition of *M. avium*-stimulated COX-2 promoter activation (Fig. 5B). However, transfection with dominant-negative TLR4 (P712H) had no effect on *M. avium*-stimulated luciferase activity (Fig. 5B). The behavior of TLR4 (P712H) as dominant-negative was validated by the observation that this mutant could inhibit LPS-driven luciferase activation (Fig. 5E), corroborating the observa-

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**Fig. 5.** *M. avium* stimulates COX-2 promoter-driven luciferase reporter expression in RAW264.7. RAW264.7 cells were transfected with the COX-2 promoter (−891 to +9)-luciferase reporter and β-galactosidase constructs. A, transfected cells were left untreated or treated with U0126 (15 μM), or SB203580 (5 μM), or H89 (10 μM), or a combination of U0126 and SB203580. Cells were then challenged for 6 h with *M. avium* or with *M. avium* preincubated with polymyxin B (10 μg/ml). In addition to the constructs mentioned above, cells were co-transfected with empty vectors or constructs as indicated; followed by challenge with *M. avium* (B) or with *E. coli* LPS (E) for 6 h. C and D, cells were transfected with the 4×κB-luciferase construct (C) or the 6×CRE-luciferase construct (D) instead of the COX-2 promoter-luciferase construct. Transfected cells were treated with inhibitors (C and D) as described above. Cells were then left untreated or incubated with *E. coli* LPS or with *M. avium* (as indicated in the panels) for 6 h. Following incubations, luciferase reporter activities in the cell extracts were measured using luciferin as substrate. In each case, the level of induction of luciferase activity was compared with that of untreated cells. The activities shown represent data that have been normalized with β-galactosidase activity. Results represent the means ± S.D. of three independent experiments.
The MAPKs ERK and p38 Regulate M. avium-induced COX-2 Expression in Macrophages

The MAPKs ERK and p38 MAPK activation on COX-2 promoter-driven luciferase expression in M. avium-challenged RAW264.7 cells, were pretreated with ERK and p38 MAPK-specific inhibitors U0126 and SB203580, respectively. Both these inhibitors caused a partial inhibition of luciferase expression (Fig. 5A). However, a combination of both inhibitors completely inhibited luciferase expression, suggesting that ERK and p38 MAPK activation are critical in sustaining M. avium-driven COX-2 promoter activation.

MSK1 Is Activated in M. avium-stimulated Macrophages—

The MAPKs phosphorylate several downstream kinases, one of which is MSK1, which is constitutively localized in the nucleus where it regulates transcription by phosphorylating histone H3, p65/RelA, and CBP/p300 (32, 33) leading to modification of nucleosome conformation and increased accessibility of the H3, p65/RelA, and CBP/p300 (32, 33) leading to modification of

the activation of MSK1. MSK1 kinase activity was determined in M. avium-treated macrophages by immunoprecipitating MSK1 from cell lysates and assaying the ability of the immunoprecipitates to phosphorylate the peptide: EILSRRPSYRK (CREB-TIDE) (34). M. avium activated MSK1 in a time-dependent manner (Fig. 6A). MSK1 activity could be partially inhibited by pretreatment with either U0126 or SB203580 (Fig. 6B), suggesting a role of both ERK and p38 MAPK signaling in MSK1 activation. A combination of U0126 and SB203580 completely blocked MSK1 activation (Fig. 6B), suggesting that ERK and p38 MAPK act synergistically to activate MSK1. The finding that both kinases are required for MSK1 activity raises the possibility that they may phosphorylate non-overlapping sites that affect the kinase activity of MSK1, or that the two kinases regulate each other, or that the activity of neither of the two kinases is sufficient to fully phosphorylate MSK1. Whatever the mechanism, our findings suggest that MSK1 plays an essential role as a downstream effector of M. avium signaling controlling both NF-κB- and CRE-driven COX-2 promoter activation. The following sections detail our attempts to address this question.

CREB Plays a Role in M. avium-induced COX-2 Promoter Activation—CREB, a member of the ATF family of transcription factors, binds to the CRE element. Because mutation of the COX-2 CRE site inhibits COX-2 reporter activity, we explored
the role of CREB in \textit{M. avium}-induced COX-2 reporter activity. Transfection of cells with dominant-negative CREB along with the COX-2-luciferase construct led to an inhibition of \textit{M. avium}-driven COX-2 promoter activity (Fig. 5B).

\textbf{CREB Is Phosphorylated in \textit{M. avium}-stimulated Macrophages—CREB is a target of MSK1 (35). We examined whether CREB phosphorylation is differentially regulated in untreated and \textit{M. avium}-challenged macrophages and whether MSK1 regulates this process. To test this, cells were transfected with wild type or dominant-negative MSK1 and challenged with \textit{M. avium}. Lysates from \textit{M. avium}-challenged and untreated macrophages were probed with an antibody that specifically recognizes CREB phosphorylated at Ser-133. Our results showed that CREB phosphorylation was enhanced in \textit{M. avium}-challenged macrophages and that this was abrogated in cells transfected with dominant-negative MSK1 (Fig. 6C).

We also examined whether the enhanced CREB phosphorylation correlated with differences in CREB-specific DNA binding. Nuclear extracts were prepared from untreated cells as well as cells treated for 3.5 h with \textit{M. avium}. Only extracts from \textit{M. avium}-treated cells showed binding to an oligonucleotide sequence corresponding to the CREB-binding site of the COX-2 promoter (Fig. 4C). DNA binding was inhibited by excess unlabeled oligonucleotide. No binding was observed when a mutant CREB-binding oligonucleotide sequence was used (data not shown). Anti-CREB antibody supershifted the band obtained with the CREB-specific DNA probe suggesting that CREB binds to the CRE element of the COX-2 promoter.

\textbf{MSK1 Is Necessary For Regulating COX-2 Promoter-driven Gene Expression in \textit{M. avium}-challenged Macrophages—To assess the effects of MSK1 on COX-2-promoter-driven luciferase expression in \textit{M. avium}-treated macrophages, cells pretreated with H89 (Fig. 5A) or transfected with dominant-negative MSK1 (Fig. 5B) were subsequently challenged with \textit{M. avium}, and luciferase gene expression was assayed. In each case, suppression of MSK1 activity led to almost complete inhibition of luciferase expression, suggesting that MSK1 plays an important role in regulating activation of the COX-2 promoter following \textit{M. avium} challenge. We further analyzed the role of \textit{M. avium}-mediated MSK1 activation on NF-\kappa B and CRE-driven luciferase expression by transfecting cells with a luciferase reporter gene fused downstream of either a 4× NF-\kappa B element or a 6× CRE element. \textit{M. avium} could activate both NF-\kappa B-driven (Fig. 5C) and CRE-driven (Fig. 5D) luciferase expression in these cells. However, such activation was abrogated in cells in which MSK1 activity was inhibited by treatment with H89. Transfection with dominant-negative MSK1 gave similar results (data not shown). These results definitively demonstrated that MSK1 regulates both NF-\kappa B- and CRE-driven gene expression triggered by \textit{M. avium}. In this regard, the effect of \textit{M. avium} was different from that observed in the case of LPS. We observed that \textit{Escherichia coli} LPS-stimulated NF-\kappa B- and CRE-driven luciferase expression (Fig. 5, C and D). The latter effect could be inhibited in cells pretreated with H89 (Fig. 5D). However, NF-\kappa B-driven luciferase expression could not be inhibited by pretreatment with U0126 or SB203580 or H89 (Fig. 5C).

\textbf{DISCUSSION}

High PGE$_2$ concentrations during mycobacterial infection cause down-regulation of cell-mediated immunity permitting disease progression (36). The immunosuppressive effects of prostaglandin E$_2$ in relation to mycobacterial infection underscore the need to understand the mechanisms regulating the expression of the rate-limiting enzyme in prostaglandin synthesis, COX-2. Animal models of tuberculosis have demonstrated that blocking of COX-2 produced high inflammation and expression of tumor necrosis factor-\alpha and interferon-\gamma. Although previous reports have shown that virulent \textit{M. avium} stimulates the expression of COX-2, the signaling pathways regulating COX-2 expression remain to be studied. The data presented in this report focus on the role of signaling pathways in \textit{M. avium}-induced COX-2 gene transcription. Our data demonstrate that \textit{M. avium}-induced gene expression driven by the COX-2 promoter depends on TLR2-dependent signaling converging on the NF-\kappa B and CRE-elements present in the promoter, but not on the C/EBP\beta or the AP-1 elements. Mutation at either the NF-\kappa B-binding site or at the CRE-binding site led to a partial inhibition of \textit{M. avium}-induced COX-2 promoter-driven luciferase gene expression (Fig. 4A), whereas mutation at both these sites completely inhibited luciferase expression. At the same time, nuclear extracts from \textit{M. avium}-challenged macrophages effected electrophoretic mobility shifts of oligonucleotides corresponding to the COX-2-gene specific NF-\kappa B and CRE sites (Fig. 4, B and C). Transcription factor NF-\kappa B has been shown to induce macrophage COX-2 in response to a variety of stimuli (37). Hee and Hwang (29) have demonstrated that LPS triggers TLR4-mediated NF-\kappa B activation leading to COX-2 gene expression. Our studies demonstrate that TLR2 contributes to \textit{M. avium}-induced COX-2 gene induction (Fig. 5). Suppressor 1B-\alpha transfection led to inhibition of COX-2 promoter activity as well as consensus NF-\kappa B-driven promoter activity (Fig. 5, B and E). These results supported a role of the canonical NF-\kappa B activation in \textit{M. avium}-stimulated COX-2 promoter activation. \textit{M. avium}-induced canonical NF-\kappa B activation was also observed by Giri et al. (38). In addition to the classic pathway, TLRs are known to activate downstream signaling cascades through small G proteins such as Rac and Ras to mediate NF-\kappa B activation. We observed that \textit{M. avium} challenge led to association of Ras with TLR2 and a

![Fig. 7. Model depicting the \textit{M. avium}-triggered signaling pathways regulating COX-2 gene expression.](image-url)
rapid activation of Ras (Fig. 2). COX-2 promoter activation, as well as activation of the consensus NF-κB promoter relied on TLR2/Ras-dependent ERK activation (Fig. 3A). In the classic Toll signaling pathway, TLRs upon recognizing suitable ligands recruit MyD88/IRAK/TRAFl. This leads to the activation of MAPK kinase kinases such as TAK1. M. avium triggered TLR2/TRAFl/TAK1-dependent p38 MAPK activation (Fig. 3D). Both ERK and p38 MAPKs were responsible for the activation of the nuclear kinase MSK1. A combination of pharmacological inhibitors of ERK and p38 completely inhibited MSK1 activation (Fig. 6B). Inhibitors of either ERK or p38 (U0126 or SB203580, respectively) partially inhibited NF-κB-driven luciferase expression, whereas H89 could block luciferase expression completely (Fig. 5C). These results clearly demonstrated that MSK1 plays an important role in M. avium-triggered NF-κB activation. This effect of M. avium on RAW264.7 macrophages was different from that reported in the case of LPS-driven COX-2 expression in RAW264.7, where LPS-driven NF-κB activation has been shown to occur independent of ERK (39) or MSK1 (8) activation. Previous work by Deak et al. (34) demonstrated that the transcription factors CREB and ATF1 are physiological substrates of MSK1. In the present study we also observed that M. avium induced phosphorylation of CREB in an MSK1-dependent manner (Fig. 6C).

In summary, M. avium triggers TLR2-dependent signaling leading to the phosphorylation of ERK and p38 MAPKs, which converge to activate MSK1 (Fig. 7). MSK1 regulates both the NF-κB and the CRE-driven gene transcription. Both phosphorylated CREB and NF-κB are known to recruit histone acetylases such as CBP/p300, which in turn contribute to making the promoter more accessible to transcription factors and help in bridging the transcription factor-CBP complexes to components of the basal transcription machinery (40). MSK1 phosphorylates histone h3 (41) and has also been identified as a nuclear kinase for p65, phosphorylating p65 at serine 276 (42). Our results point to the fact that MSK1-dependent changes, likely at the level of the nucleosome, are prerequisite for M. avium-driven COX-2 gene expression. The nature of nucleosome remodeling following M. avium infection is presently under investigation.

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