Coordinate Activation of Activator Protein 1 and Inflammatory Cytokines in Response to Neisseria gonorrhoeae Epithelial Cell Contact Involves Stress Response Kinases

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Summary

Neisseria gonorrhoeae (Ngo), the etiologic agent of gonorrhea, induce a number of proinflammatory cytokines by contact to epithelial cells. Cytokine genes and a variety of other immune response genes are activated as a result of the regulatory function of immediate early response transcription factors including activator protein 1 (AP-1). Since it is established that phosphorylation of c-Jun, the central component of AP-1, by the stress-activated c-Jun N H₂-terminal kinase (JNK) increases the transcriptional activity of AP-1, we studied whether Ngo could induce stress response pathways involving JNK. We found that virulent Ngo strains induce phosphorylation and activation of JNK but not of p38 kinase. Analysis of a nonpathogenic Ngo strain revealed only weak JNK activation. In respect to the molecular components upstream of the JNK signaling cascade, we show that a dominant negative mutant of MAP kinase kinase 4 (MKK4) represses transcription of an AP-1–dependent reporter gene. Regarding upstream stress response factors involved in Ngo-induced MKK4/JNK/AP-1 activation, we identified p21-activated kinase (PAK) but not MAPK/ERK kinase kinase (MEKK1). Inhibition of small GTPases including Rac1 and Cdc42 by Toxin B prevented JNK and AP-1 activation. Our results indicate that Ngo induce the activation of proinflammatory cytokines via a cascade of cellular stress response kinases involving PAK, which directs the signal from the Rho family of small GTPases to JNK/AP-1 activation.

Key words: Neisseria • inflammation • activator protein 1 • c-Jun N H₂-terminal kinase • p21-activated kinase

The production of immunostimulatory cytokines by epithelial cells is an essential part of the biological response to the infection with human pathogenic microorganisms (1). Any inflammatory reaction requires the de novo synthesis of defined proteins. These include chemokines that attract macrophages and inflammatory cytokines that serve to amplify and spread the primary pathogenic signal. The mechanism by which these proteins are newly synthesized involves an inducible transcriptional initiation of their respective genes. This is governed by several transcription factors playing a role in regulating immune response genes including the early transcription factor activator protein 1 (AP-1; reference 2).¹

¹Abbreviations used in this paper: AP-1, activator protein 1; ASM, acidic sphingomyelinase; CRIB, Cdc42/Rac interactive binding; DAG, diacylglycerol; DN, dominant negative; EGF, epidermal growth factor; ERK, extracellular signal-regulated kinase; HSP, heparan-sulfate proteoglycan; JNK, c-Jun N H₂-terminal kinase; MAP, mitogen-activated protein; MAPK, MAP kinase; MEK, MAP/ERK; MEKK, MEK kinase; MKK, MAP kinase; M KK, M KK kinase; M KK, M KK kinase; M OI, multiplicities of infection; NF-κB, nuclear factor κB; Ngo, Neisseria gonorrhoeae; PAK, p21-activated kinase; PLC, phosphatidylcholine–dependent phospholipase C; SAPK, stress-activated protein kinase.

Human pathogenic Neisseria gonorrhoeae (Ngo) induce a number of cytokine genes in epithelial cells involving the activity of the transcription factor AP-1 (3). The natural host benefit of cytokine release in response to pathogen infection is exploited by Ngo which cause a massive localized inflammation characterized by the infiltration of polymorphonuclear leukocytes and mononuclear phagocytes into the infected tissue of the urethra or the endocervix (4). As a consequence, the infected epithelial cell layer is destroyed and the bacteria may gain better access to deeper tissues (5). The colonization of the epithelia is a prerequisite of infection by Ngo and is largely dependent on the expression of a set of variable surface proteins. The hair-like type 4 pili
mediate the first contact between bacteria and host cells and are indispensable for infection in vivo (6, 7). Variant outer membrane proteins of the opacity-associated outer membrane protein family (Opa proteins) tightly interact with the host cell surface and trigger the engulfment of N. gonorrhoeae (8). There are at least three independent routes by which Opa proteins induce the uptake of N. gonorrhoeae into host cells each mediated by interaction with a certain receptor. Heparan-sulfate proteoglycan (HSP) receptors (9) or the concerted action of HSPR and integrin receptors (10, 11) account for the major pathways for uptake into epithelial cells. Uptake of N. gonorrhoeae by the HSPR pathway involves the action of phosphatidylincholine-dependent phospholipase C (PLC) and the acidic sphingomyelinase (ASM) (12). The HSPR–integrin pathway possibly PKC (11). In phagocytic cells, Opa proteins occupy receptors of the CD 66 family that results in a rapid, opsonin-independent phagocytosis of N. gonorrhoeae (13–15) involving Src kinases and Rac1 (16).

In contrast to the well-studied Neisseria adherence and invasion process, very little is known about the nature of the pathogen-induced proinflammatory signals. Our previous results showed that the infection of epithelial cells with gonococci induced the activation of the transcription factor AP-1 (3). In line with the known immunostimulatory function of AP-1 and nuclear factor κB (NF-κB; references 17, 18) epithelial cells infected with N. gonorrhoeae produced increased amounts of numerous proinflammatory cytokines (3). The secretion of cytokines in the cultured epithelial cell model was not initiated by LPS suggesting that the endotoxin-mediated mechanisms known to trigger inflammatory reactions of lymphoid cells are not relevant for epithelial cells (3). However, neither the signals nor the signaling pathways activating AP-1, which lead to production of cytokines in N. gonorrhoeae-infected epithelial cells, are defined.

Environmental stress or engagement of cytokine receptors leads to the activation of AP-1 and a family of mitogen-activated protein kinases (MAPK), which consecutively activate their members by phosphorylation (18, 19). In such a cascade, the AP-1 subunit c-Jun is activated by MKKK beside MEKK1 have recently been identified, all activating activity of AP-1, HeLa cells at 50–70% confluence were cotransfected by cationic liposomes (Promega) with 1 µg of a luciferase expression plasmid containing three repeats of the AP-1 binding site as an enhancer element and expression constructs: dominant negative MEKK1 (K432M), dominant negative MEKK4 (M KK4, M KK7), and M KK4 is activated by MAP/ERK (extracellular signal-regulated kinase) kinase 1 (MEKK1) at the level of MAPK, M KK, and MKK kinase (M KK), respectively. Numerous M KK beside MEKK1 have recently been identified, all able to activate the JNK pathway (20–25). The reason why mammalian cells express so many M KK involved in signaling to stress-activated transcription factors is still unknown. It is still unclear in particular how the M KK themselves are activated in mammalian cells in response to stress signals or cytokine receptor activation.

The small GTPases Rac1 and Cdc42 have been identified as far upstream regulators of the JNK kinase cascade (20, 26, 27). The p21-activated kinases (PAKs) were the first kinases identified as direct effectors for the active GTPases Rac1 and Cdc42 (28). GTP-loaded Rac1 or Cdc42 bind to a Cdc42/Rac interactive binding (CRIB) domain (29) and thereby increase the activity of PAK significantly (28). Recently, M EKK1 and M EKK4 have also been shown to interact with Rac and Cdc42 (30). Blocking either PAK or M EKK1 activity prevents the activation of J N K either in response to activated GTPases (30, 31) or to apoptotic stimuli independent of GT Pases (31, 32). However, blocking M EKK kinase does not prevent JNK activation by active PAK suggesting that both classes of kinases signal independently.

We show that N. gonorrhoeae induces the activation of the AP-1 transcription factor by a distinct kinase cascade involving GT Pases, PAK, M K K4, and J N K1, but not M EKK1. The identification of pathogen-specific signaling pathways to inflammatory cytokine production might be a basis for the therapeutic intervention of infections.

Materials and Methods

Human Cell Culture and Infection. Epithelial cells (HeLa and Chang) were grown in RPMI 1640 (GIBCO BRL, Gaithersburg, MD) supplemented with 4 mM glucose, 100 IU/ml penicillin, 100 µg/ml streptomycin, and 10% FCS in a humidified 5% CO2 atmosphere. Epithelial cells were seeded in tissue culture plates for 48 h before infection. 16 h before infection, the medium was replaced by fresh RPMI 1640 medium supplemented with 10% FCS. The epithelial cells were infected with N. gonorrhoeae given in multiplicities of infection (MOI) as described in the figure legends for different periods of time. For infection experiments, bacteria were centrifuged onto the epithelial cell monolayer for 5 min at 500 g. In the experiments using 10–50 ng/ml Toxin B (supplied by F. Hofmann and K. Aktories, University of Freiburg, Freiburg, Germany), the cells were preincubated for 15 min before the bacteria were added. Stimulation of the cells with 10 ng/ml TNF-α (Promega, Heidelberg, Germany) or 50 nM PMA (Sigma Chemical Co., St. Louis, MO) was performed for the indicated time points.

Bacteria. Three different N. gonorrhoeae strains were used for infection of human epithelial cell lines: the nonpiliated, but invasive Opa2 strain N242, (VP1, P1A, P7, Opa2, Opa2, Opa2, Opa2, Opa2, lipopolysaccharide type L1) has been described (8). The adherent but non invasive Pstrain N138 (P, P, PilE1 and the P- strain control strain N300 (P, PilE1, Opa, Opa) are derivatives of strain M511 (34, 35). Gonococci were routinely grown on GC phosphate agar as described previously (36). Strain N242 was also grown in RPMI 1640 containing 25 mM Hepes, pH 7.2, for 2 h at 37°C before infection.

Transfections and Luciferase Reporter Assays. To measure the trans-activating activity of AP-1, HeLa cells at 50–70% confluence were cotransfected by cationic liposomes (Promega) with 1 µg of a luciferase expression plasmid containing three repeats of the AP-1 binding site as an enhancer element and expression constructs: dominant negative MEKK1 (K432M), dominant negative MEKK4 (M KK4, M KK7), and P- control strain N300 (P, PilE1, Opa, Opa, Opa) are derivatives of strain M511 (34, 35). Gonococci were routinely grown on GC phosphate agar as described previously (36). Strain N242 was also grown in RPMI 1640 containing 25 mM Hepes, pH 7.2, for 2 h at 37°C before infection.

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solid-phase kinase assays using appropriate substrates were

for immunoprecipitation of the endogenous kinases and

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of epithelial cells. Strain N 138 (P + Opa−) expresses

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of N 138 (P + Opa−; Fig. 1, top) within 15 min after in-
fication. The immediate JNK1 induction was followed by a

sustained JNK1 kinase activation for at least 90 min. Acti-
vation of JNK1 in Chang epithelial cells was at least 10
times weaker than in HeLa cells, probably due to lower

adherence levels of N go to Chang cells. To test whether

cellular JNK1 activation is at variance in epithelial cells

infected with adherent versus invasive N go strains, we com-
pared JNK1 kinase activity in HeLa cells and Chang cells

infected either with the P + or Opa− strain. At a MOI of

50, the invasive Opa− strain induced a slightly stronger ac-
tivation of JNK1 activity than the P + strain, whereas weak

JNK1 activation was observed in cells treated with the

nonpathogenic strain N 300 (P − Opa−) or LPS. The activa-
tion of JNK1 in response to N go was delayed compared to

the JNK1 induction in TNF-α–treated cells, but showed a

similar potential to induce JNK1 activity. The lower panel

shows a Western blot probed with an anti-JNK1 antibody,
to show similar protein amounts in all lanes. Weak activa-
tion of JNK2 was observed in HeLa cells in response to

N go infection (data not shown). In contrast to JNK1, we

did not detect any p38 induction paralleled with JNK1 ac-
tivation (data not shown).

DNMKK4 Inhibits N go-mediated Induction of AP-1. Be-
sides the various stimuli (growth factors, UV light irradia-
tion, cytokines, protein synthesis inhibitors, etc.) that could

induce the JNK cascade (19), pathogens represent new po-

\[ \text{RIPA buffer as described previously (37). For PAK, cells were }

\text{lysed in 50 mM Tris, pH 7.5, 1 mM EGTA, 5 mM MgCl}_2,

\text{1% N P-40, 2.5% glycerol, 150 mM NaCl, 1 mM NaVO}_4,

\text{10 mM Na}_2\text{PO}_4, 50 mM NaF, 100 μM PM SF, 10 μM }

\text{Peptatin A, and 4 μM Aprotinin. The cells were disrupted by }

\text{passing the lystate several times through a 21-gauge syringe.}

\text{The cell debris was collected by centrifugation and the }

\text{supernatants were incubated with the appropriate antiseras }

\text{(Santa Cruz Biotechnology, Santa Cruz, CA) coupled to protein A–}

\text{or G-Sepharose (Amersh}

\text{am Biotechnology Inc., Piscataway, NJ). The antiseras were }

\text{coupled to the protein A or G beads in PBS for 1 h at 4°C. In }

\text{a first preadsorption step the supernatants were incubated with }

\text{protein A or G beads alone for 1 h at 4°C. After this preadsorp-

\text{tion the supernatants were incubated with the appropriate antiseras }

\text{for 2-3 h at 4°C. Immunocomplexes were recovered and }

\text{washed several times with RIPA buffer and twice with kinase buffer. }

\text{Immunoprecipitates of JNK were resuspended in 30 μl of kinase }

\text{buffer containing 100 mM KCl, 0.1 mM CaCl}_2, 6 mM MgCl}_2,

\text{30 mM Tris, pH 7.5, 0.1 mM NaVO}_4, 10 mM K_2\text{HPO}_4,

\text{10 mM NaF, 1 mM DTT, and 1 μg of the substrate (GST-c-Jun }

\text{for JNK, GST-ATF2 for p38; Santa Cruz Biotechnology). Immuno-

\text{precipitates of PAK were resuspended in 30 μl of kinase }

\text{buffer containing 100 mM Hepes, pH 7.5, 10 mM MgCl}_2,

\text{2 mM MnCl}_2, 0.2 mM dithiothreitol, 0.1 mM NaVO}_4,

\text{14 mM ATP, and 1 μg of myelin basic protein (MBP; Sigma }

\text{Chemical Co.). The kinase reactions were initiated by addition of 10 μM }

\text{Ca}^{2+}-

\text{ATP (5,000 Ci/mmol; Amersham Pharamacia Biotechnolo-

\text{gy Inc.). After 30 min incubation at 30°C, reactions were }

\text{terminated by adding SDS loading buffer. Samples were separated }

\text{by SDS-PAGE, blotted, and developed as described (38) to show }

\text{similar protein amounts in all lanes. After immunostaining }

\text{the blots were analyzed further by autoradiography or PhosphorIm-

\text{ager analysis.}}


\section*{Results}

A division of JNK in response to N go-Epithelial Cell Con-

tact. In our previous report, we showed that the early response

transcription factor AP-1 and inflammatory cytokine gene

expression are coordinately induced in N go infected epithe-

lial cells (3). Activation of the dimeric sequence specific enhan-

cer factor AP-1 is mediated through phosphorylation of c-Jun by members of the MAPK family. Therefore, we ex-

amined whether the JNKs and/or p38, also known as stress

activated kinases (39–41) are involved in the signaling lead-

ing to N go-induced AP-1 activation and inflammatory cy-

tokine gene expression. Cell lysates from N go-infected ep-

ithelial cells were used at different time points after infection

for immunoprecipitation of the endogenous kinases and

solid-phase kinase assays using appropriate substrates were

performed. The N go strains tested differed with regard to the

infection of epithelial cells. Strain N 138 (P + Opa−) expresses

pili that confer adherence to epithelial cells, but does not

express any Opa proteins and therefore is not invasive (42).

Strain N 242 (Opa−) enters epithelial cells by binding to

heparan sulfate containing surface proteoglycan receptor

proteins (8, 9). Strain N 300 (P − Opa−) is neither piliated,

nor does it express Opa proteins (35) and, hence, is a very

weak adherent. Infection with N go strains was routinely

monitored by light microscopy.

The activity of JNK1 was induced several fold in sub-

confluent monolayers of HeLa cells by adherence of N go

strain N 138 (P + Opa−; Fig. 1, top) within 15 min after in-
fection. The immediate JNK1 induction was followed by a

sustained JNK1 kinase activation for at least 90 min. Acti-

vation of JNK1 in Chang epithelial cells was at least 10

times weaker than in HeLa cells, probably due to lower

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sides the various stimuli (growth factors, UV light irradia-
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...
tent inducers in this regard. Thus it is a challenge to understand whether pathogens inducing inflammation use similar or different signaling pathways compared to known stimuli. For JNK, MKK4/SEK1 (stress-activated protein kinase/extracellular-regulated kinase 1 [SAPK/ERK]) has been identified as a direct activator, phosphorylating JNK at threonine and tyrosine residue in the motif TPY (43-45).

In addition, recent studies using sek1^{-/-} cells indicated that there are MKK4/SEK1-dependent and MKK4/SEK1-independent signaling pathways for JNK activation (46, 47).

To address the possible role of MKK4 in N. gonorrhoeae-induced transcriptional activity of AP-1, we examined the effect of inhibitory DNMKK4 on the transcription of an AP-1-dependent reporter construct (Fig. 2). In transient transfection assays the overexpressed DNMKK4 significantly inhibited P^+ Opa^- and P^- Opa^+ induced AP-1-dependent reporter gene expression (Fig. 2, A and B), but not of an N-F-kB-dependent reporter gene (data not shown). This is in agreement with the earlier observation that the JNK activa-
tion is not linked to N-F-kB activation (48, 49). Similarly, PMA induced AP-1 activation was blocked by DNMKK4 (Fig. 2 D). N. gonorrheae strain P^+ Opa^- did not induce AP-1 transcription activity (Fig. 2 C). The strong inhibitory effect of DNMKK4 on pathogenic N. gonorrhoeae and PMA induced AP-1 activation indicates a major role of MKK4 for the JNK-MAPK signal transduction pathway. DNMKK4 might inhibit N. gonorrhoeae-induced signal transduction pathways, in which MKK4 is intimately involved by strongly interacting with its upstream activators and/or its downstream elements.

Toxin B inhibits AP-1 and JNK activation in N. gonorrhoeae-stimulated cells. Attachment of epithelial cells by N. gonorrhoeae suggests the involvement of cytoskeletal rearrangements (36) as shown for Helicobacter pylori (50) and other pathogenic microbes (51). Cytoskeletal rearrangements are known to be regulated by small GTPases of the Ras family (52). Therefore, we studied whether GTPases were involved in N. gonorrhoeae-induced signaling pathways leading to JNK and AP-1 activation. The GTPases Ras, Cdc42, and Rac1 have been identified as important intermediates to the JNK signaling cascades (20, 27, 53). The activity of Ras and GTAPases not of Ras is specifically inhibited by enterotoxin Toxin B from Clostridium difficile, which glycosylates and inactivates Cdc42, Rac1, and Rac (54, 55). Pretreatment of HeLa cells for 15 min with 10 ng/ml Toxin B is sufficient to reduce AP-1 transactivation activity in the presence of adherent N. gonorrhoeae strain (P^+ Opa^-) to the baseline levels (Fig. 3, compare right and left panel) indicating the involvement of Rho-GTPases in N. gonorrhoeae-induced AP-1 activation. As a control we studied the PMA-induced AP-1-dependent reporter activity, which appears not to be affected by Toxin B (Fig. 3). Similar to AP-1, JNK activation (assayed in an in vitro kinase assay) in response to the adherent N. gonorrhoeae strain (P^- Opa^+) was inhibited in the presence of Toxin B (Fig. 4, lanes 1 and 3 versus 4 and 6). Treatment of HeLa cells with Toxin B already induces JNK activity (Fig. 4, lanes 1 and 4). In contrast to N. gonorrhoeae-stimulated cells could induce JNK activity in Toxin B-treated cells (Fig. 4, lanes 1, 2, 4, and 5).

AP-1 activation in N. gonorrhoeae-stimulated epithelial cells involves PAK signaling. There are potentially many different kinases that could contribute to small GTPase-mediated JNK and AP-1 activation. The most prominent kinases acting downstream of Ras-GTPases are the PAKs (p21-activated kinases) and the MEKK (56). The PAKs show homology and AP-1 activation. The most prominent kinases acting downstream of Rho-GTPases are the PAKs (p21-activated kinases) and the MEKK (56). The PAKs show homology and AP-1 activation. The most prominent kinases acting downstream of Rho-GTPases are the PAKs (p21-activated kinases) and the MEKK (56). The PAKs show homology

![Figure 2](https://rupress.org/jem/article-pdf/188/7/1277/973976/98-0991.pdf) Inhibition of AP-1 transactivation activity by dominant inhibitory MKK4. HeLa cells were transfected with 1 mg reporter construct containing three repeats of the AP-1 binding site and either 1 mg dominant inhibitory MKK4 (DNMKK4) or empty vector. After overnight incubation with the DNA, cells were infected with different N. gonorrhoeae strains (P^+ Opa^-, P^- Opa^+, and P^- Opa^-; A-C) at a MOI of 50 or treated with 50 nM PMA (D) for the indicated periods of time. The results of a representative experiment are expressed as fold induction compared with the activity observed with transfection of the reporter vector and empty vector, and in the absence of N. gonorrhoeae or PMA. Similar results were obtained in more than three independent experiments.

![Figure 3](https://rupress.org/jem/article-pdf/188/7/1277/973976/98-0991.pdf) Toxin B inhibits N. gonorrhoeae-induced AP-1 activation. HeLa cells were transfected with 1 mg reporter construct and after overnight incubation, cells were treated with 10 ng/ml Toxin B 15 min before the infection with N. gonorrhoeae strain P^- Opa^- at a MOI of 50, or with 50 nM PMA for 30 min, respectively (right). As a control, cells were left without Toxin B (left). The results from a representative experiment are expressed as fold induction compared with the activity observed with transfection of the reporter vector and in the absence of Toxin B, N. gonorrhoeae strain, or PMA. Similar results were obtained in more than three independent experiments.
Rac1-mediated activation of MEKK (26, 27). Recent results show that MEKK1 directly interacts with Rac1 and Cdc42 (30), indicating that PAK and MEKK1 independently associate with Rho-GTPases. To examine whether PAK or MEKK1 are involved in transcriptional responses characteristic of N. gonorrhoeae, we compared their capacity to contribute to N. gonorrhoeae-induced AP-1 activation.

In transient transfection assays we used PAK2 and PAK1 dominant inhibitory mutant kinases to investigate whether PAK might be involved upstream in the N. gonorrhoeae-induced signaling cascade leading to MEKK4, JNK, and AP-1 activation. The PAK2 mutant contains a K278R and PAK1 a K299R mutation that inactivate the catalytic activity of the kinase domain. The mutations in the amino acids 278 and 299 have been demonstrated to be important for the kinase activity of PAKs (58). HeLa cells transfected with DNPAK2 and treated either with adherent (P-Opapa) or invasive (P-Opapa) N. gonorrhoeae strains for 30 min strongly reduced the AP-1 transactivation activity, compared to mock-transfected cells (Fig. 5A). Similar to PAK2 we observed reduced transactivation activity of AP-1 in transfected DNPAK1 and N. gonorrhoeae-stimulated cells (data not shown). The experiments were performed after careful titration of the cDNAs to allow specific inhibition of the AP-1 transactivation activity. Since mammalian PAKs (PAK1, 2 and 3) exert >90% homology in their COOH-terminal kinase domain, they will putatively inhibit downstream signaling of all three PAK isoenzymes. To exclude potential effects on the putative upstream components due to titration of Rho-GTPases, we performed experiments with a PAK1 construct mutated in histidine 83 and 86, which prevent the binding of GT-Pases. Using such construct, similar results as described above were obtained (data not shown). Therefore, these results indicate that PAK could lie upstream of MEKK4 and JNK leading to AP-1 activation. As already shown in Fig. 2C, nonpathogenic N. gonorrhoeae strain P0p0 slightly induces the transactivation activity of AP-1, which is reduced in DNPAK2-transfected cells. In PMA-treated cells, AP-1 transactivation activity was substantially increased but unaffected in DNPAK2-transfected cells (Fig. 5A) suggesting that PMA induces JNK/AP-1 activation via a PAK-independent pathway, as previously shown by Rudel et al. (33).

To address the possible role of wild-type PAK in transcriptional activity of AP-1 in response to N. gonorrhoeae (P+Opapa−), we examined the effect of expression of PAK on the transcription of an AP-1-dependent reporter construct. Overexpression of PAK2 (wtpPAK2) slightly enhanced transcription of an AP-1-dependent reporter gene in the absence of N. gonorrhoeae (Fig. 5B). Similar data were obtained using a wild-type PAK1 construct (data not shown). This may be in agreement with the recent observation that the PAK activation depends on active GT-Pases (28) and confirms previous data showing small JNK protein kinase activity of wild-
type PAK3 overexpression (20). In the presence of N. gonorrhoeae (P+ Opa−) we observed an increased and additive effect on the AP-1 transactivation activity compared to mock transfected cells (Fig. 5 B).

To study the JNK/AP-1 activation by the kinase activity of PAK2, we immunoprecipitated PAK2 from N. gonorrhoeae (P+ Opa−)-stimulated HeLa cells after the indicated periods of time. The activity of PAK2 (p-PAK2) was induced several fold in HeLa cells by the N. gonorrhoeae strain N138 (P+ Opa−; Fig. 5 C) within 15 min after infection measuring phosphorylation activity of PAK2 with MBP as a substrate. The immediate PAK2 induction further increased within 45 min and declined to a reduced activity within 90 min. The lower panel of Fig. 5 shows the Western blot probed with an anti-PAK2 antibody, to show similar protein amounts in all lanes.

In an attempt to explore whether MEKK1 is involved when N. gonorrhoeae induce MKK4/JNK/AP-1 activity, we tested if inhibitory DNMEKK1 blocks this pathway. In contrast to kinase-inactive inhibitory mutants of PAKs, DNMEKK1 does not block N. gonorrhoeae-induced AP-1 transcription activity (Fig. 6, A and B). In contrast to N. gonorrhoeae, PMA-induced AP-1 transcription activity clearly appears inhibited by DNMEKK1 (Fig. 6 C). A role for PMA-activated PKC in the activation of MEKK1 was recently described (59).

Therefore, these results indicate that PAKs do not lie upstream of MEKK1 in a pathway leading to AP-1 activation. Rather, the data suggest that PAKs independently mediate JNK/AP-1 activation in a N. gonorrhoeae-induced signaling pathway.

Discussion

In most pathogen infections, epithelial cells represent the first barrier for the microorganisms in the host tissue and could function as an early warning system that activates the immune response using signals that lead to the attraction of phagocytic cells (1). The activatory signaling leading to posttranslational modification and activation of the transcription factor AP-1 plays a critical role in the regulation of proinflammatory cytokine genes and other gene promoters whose gene products have immunomodulatory functions (60). The ability to respond appropriately to such signaling events is essential for the survival of the eukaryotic cell. Perturbations in the normal regulation of these specific responses can result in pathogenic events that lead to acute or chronic disease. AP-1 transcriptional activity and subsequent upregulation of proinflammatory cytokines is induced upon the initial contact of Neisseria gonorrhoeae with epithelial cells, which influence the immune surveillance. Adherent P+ N. gonorrhoeae or invasive Opa− N. gonorrhoeae induce a rapid and specific activation of AP-1 and subsequently a panel of cytokine genes. The physical invasion of epithelial cells by N. gonorrhoeae is not a prerequisite of AP-1 activation and cytokine upregulation (3). Thus, it appears that the N. gonorrhoeae-eukaryotic cell contact is already sufficient to induce an efficient downstream signaling. To a better understanding of the crucial outcome of the N. gonorrhoeae infection, we studied the upstream components involved in AP-1 activation.

In this study we analyzed the capability of adherent and invasive N. gonorrhoeae strains to induce stress response kinase pathways leading to AP-1 activation in epithelial cells. Components of kinase cascades modulate AP-1 activation at different control points including regulation at the transcriptional and posttranslational level. Exposure of mammalian cells to a variety of physiological stress stimuli, including N. gonorrhoeae contact (3), activate the transcription factor AP-1 and many target genes (19). Moreover, overexpression of AP-1 in response to a variety of stress factors has been implicated in a number of immunoinflammatory and proliferative diseases (60). c-Jun is the central component of all AP-1 dimeric protein complexes and phosphorylation of c-Jun in the activation domain is exerted only by the JNKs (19). We found that N. gonorrhoeae stimulates JNK in epithelial cells (Fig. 1), which phosphorylates c-Jun at serines 63/73 (61), and AP-1-dependent transcriptional activity (Fig. 2). The JNK kinase activity in response to adherent (P+ Opa−) or invasive (P− Opa+) N. gonorrhoeae strains, which induce a variety of proinflammatory cytokines, was observed rapidly within 15 min after infection at a M.O.I of 50 and further increased within 90 min, whereas the nonpathogenic strain (P− Opa−) or LPS induced weak and no JNK activity, respectively. Our data indicate that contact between N. gonorrhoeae and epithelial cells is sufficient to induce an efficient downstream signaling leading
to the activation of cytokine genes. The TNF-α-treated cells showed JNK activation to a similar extent, but with a maximum within 15 min. Activation of JNK was observed in both cell lines studied, but was at least 10 times less effective and delayed in Chang cells compared to HeLa cells. This points to the assumption that epithelial cells are capable of responding differently to external stimuli. For example, the opa-dependent invasion of N go in Chang conjunctiva cells occurs irrespective of the presence of serum but involves PLC and ASM (12). In many other epithelial cells, this signaling pathway appears to be less prominent, whereas the serum factor vitronectin was shown to allow HSPR-dependent invasion (10). The observation that JNK, but not p38 kinase was activated by N go suggests that the activatory mechanisms of these kinases by this stimulus are at least partially different. Our finding that N go induced stress response kinase JNK contributing in the activation of cytokine genes in epithelial cells is consistent with another report on Salmonella typhimurium (62), which supports the notion that epithelial cells are an integral component of the host immune system. LPS does not effectively induce cytokines AP-1 and JNK in epithelial cells, which could be explained in part by lack of CD14 on epithelial cells. In contrast to N go epithelial cell contact, infection of macrophages by Yersinia enterocolitica suppresses the LPS-mediated activation of JNK as well as p38 kinase activation (63). Thus, different pathogen stimulators trigger multiple signal transduction pathways in the target cell.

Stimulation of cells with epidermal growth factor (EGF; references 43–45) or IL-1 (64) leads to JNK activation by a pathway that involves the activation of M KK4. Like other physiologic stress inducers (e.g., UV light and osmotic shock; reference 2), the human pathogenic adherent (P + O pa−) or invasive (P−O pa+) N go strains also induce M KK4, and overexpression of the kinase negative M KK4 inhibits activation of AP-1 (Fig. 2, A and B). The dominant inhibitory effect of M KK4 on N go-induced AP-1 activation indicates that JNK is required to mediate full transcriptional activation of AP-1 in response to N go and suggests either the formation of a stable JNK/M KK4 complex or sequestration of crucial elements immediately upstream of M KK4. A number of kinases have been postulated to regulate the activity of MKKK. The signaling pathway is shown in Fig. 5. In the future it will be necessary to address which components downstream of PAKs lead to JNK/AP-1 activation. A suggested candidate kinase that might play such a role could be SPRK, a mixed lineage kinase (23). p21-activated kinase is the most upstream component of the R ac1/C dc42 pathway linking these GTPases to JNK (56). By studying the involvement of GTPases in N go-induced signaling, we used Toxin B from Clostridium difficile, which specifically inhibits the activity of the members of the Rho family (54). AP-1 transcriptional activity and JNK activation is strongly reduced in the presence of Toxin B (Fig. 3). These data indicate that GTPases and PAKs may function as components of the same signal transduction pathway that leads to JNK protein kinase and the activation of the transcription factor AP-1.

From these findings, we suggest a pathway, depicted in Fig. 7, through which human pathogenic N go stimulate the JNK/AP-1 activity. Activation of GTPases by upstream signals leads to increased activity of PAK kinase(s). PAK does not directly phosphorylate JNK. Activation of JNK by N go requires dual phosphorylation by M KK4, which becomes phosphorylated by M KK K. Thus PAKs presumably regulate the activity of M KK K. The signaling pathway through GTPases, PAK, M KK K, p38, and AP-1 are orchestrated to yield a coordinated response of cytoskeletal changes and transcriptional activity leading to the release of immune response mediators.

N. gonorrhoeae strains used in our experiments produce either pili (P+) or Opa proteins (P0pa+) capable of interacting with cells or neither pil nor Opa proteins. In phagocytes the Opa-C D66 receptor interaction could be important for the invasion-dependent downstream signaling involving Src-kinases and R ac1 (16). Internalization of Opa-expressing N go in epithelial cells has been shown to be HSP-dependent (9) and occur by at least two different mechanisms. Invasion in Chang cells depends on the activation of ASM and the second messengers diacylglycerol (DAG) and...
ceramide (12). In other epithelial cells including HeLa, another pathway depending on the serum factor vitronectin allows HSP-dependent invasion. Vitronectin-dependent invasion of Op a does not involve integrin receptors (11). Vitronectin also possesses a HSP-binding site and is generally known to interact with certain integrins (71). In this respect internalization of N go by epithelial cells could be mediated by integrin-dependent endocytosis of vitronectin, which results from interaction with heparan-sulfate proteoglycans (HSPGs). Since N go-induced cytokines, the activation of AP-1 (3) and stress response kinases are already induced by noninvasive N go (P° Opa°), we suggest that N go adhesion activates signals leading to the activation of immune response mediators. Thus it seems, that N go triggers a number of signaling pathways, which are either essential for the pathogenic infection, or represent the host reaction in response to the pathogenic microbes.

Cytokines produced from epithelial cells represent specific modulators of the immune response and could be an advantage in the eradication of the parasite, but could also be a disadvantage by leading to chronic inflammatory diseases instead. The ability to respond appropriately to such signaling events is essential for the survival of the cell and ultimately the whole organism. A chronic inflammatory state, induction of adhesion molecules, chemotaxis and activation of leukocytes, the production of mediators of inflammation and continuous T cell activation leads to self-perpetuating destruction of the epithelial structure. All these events are controlled at the level of transcription of genes necessary for the production of new proteins such as growth factors, interleukins, proteases and cytokines. Regulating this process, e.g., by disrupting the signal transduction pathways of transcription factors, has the potential to attenuate the production of immune response mediators, thereby halting or reversing the course of the disease.

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