Aspirin inhibits Chlamydia pneumoniae-induced NF-κB activation, cyclo-oxygenase-2 expression and prostaglandin E₂ synthesis and attenuates chlamydial growth

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Infection with Chlamydia pneumoniae has been implicated as a potential risk factor for atherosclerosis. This study was designed to investigate the mechanisms of the anti-chlamydial activity of aspirin. A reporter gene assay for NF-κB activity, immunoblot analysis for cyclo-oxygenase (COX)-2 and radioimmunoassay for prostaglandin E₂ (PGE₂) were performed. Following infection of HEp-2 cells with C. pneumoniae, NF-κB was activated, COX-2 was induced and PGE₂ was elevated. Aspirin inhibited NF-κB activation at a concentration of 0·1 mM, partially inhibited COX-2 induction and blocked PGE₂ synthesis completely. In addition, high doses of aspirin (1 and 2 mM) inhibited chlamydial growth in HEp-2 cells, decreasing the number and size of inclusion bodies; this effect could be overcome by adding tryptophan to the culture. Indomethacin also blocked the synthesis of PGE₂, but had no effect on COX-2 expression or chlamydial growth. These results indicate that aspirin not only has an anti-inflammatory activity through prevention of NF-κB activation but also has anti-chlamydial activity at high doses, possibly through depletion of tryptophan in HEp-2 cells.

INTRODUCTION

Chlamydia pneumoniae, a Gram-negative obligate intracellular bacterium, is known to be a respiratory pathogen (Grayston, 1992; Grayston et al., 1986, 1990). This microorganism can cause chronic infection and has recently been linked to atherosclerotic disease. Since Saikku et al. (1988) first reported serological evidence of an association between C. pneumoniae and coronary heart disease, a number of serological investigations have shown a positive relationship between C. pneumoniae infection and cardiovascular and cerebrovascular diseases (Cook et al., 1998; Miyashita et al., 1998; Wimmer et al., 1996), such as carotid atherosclerosis (Melnick et al., 1993). Furthermore, C. pneumoniae has been detected in atherosclerotic but not normal arteries by several techniques (Kuo et al., 1993; Ouchi et al., 1998; Shor et al., 1992; Yamashita et al., 1998) and isolated from coronary (Ramirez, 1996) and carotid (Jackson et al., 1997) atheromas. These findings suggest that chronic C. pneumoniae infection might be a trigger and/or enhancer of inflammatory reactions in the vessel wall and thus a causative agent of atherosclerosis.

Several lines of evidence indicate that the dimeric transcription factor NF-κB plays an important role in atherosclerosis (Brand et al., 1996; Collins, 1993; Dichtl et al., 1999; Gawaz et al., 1998; Ross, 1993). NF-κB controls the expression of various genes involved in inflammation and proliferation, such as intercellular adhesion molecule-1 (ICAM-1) (Baeuerle & Henkel, 1994; Dichtl et al., 1999; Poston et al., 1992), vascular cell adhesion molecule-1 (VCAM-1) (Cybulsky & Gimbrone, 1991; Dichtl et al., 1999; Neish et al., 1998; Wimmer et al., 1996), such as carotid atherosclerosis (Melnick et al., 1993). Furthermore, C. pneumoniae has been detected in atherosclerotic but not normal arteries by several techniques (Kuo et al., 1993; Ouchi et al., 1998; Shor et al., 1992; Yamashita et al., 1998) and isolated from coronary (Ramirez, 1996) and carotid (Jackson et al., 1997) atheromas. These findings suggest that chronic C. pneumoniae infection might be a trigger and/or enhancer of inflammatory reactions in the vessel wall and thus a causative agent of atherosclerosis.

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al., 1992), cyclo-oxygenase-2 (COX-2) (Appleye et al., 1994; D’Acquisto et al., 1997; Pistritto et al., 1999) and inducible nitric oxide synthase (iNOS) (Chu et al., 1998; Marks-Konczalik et al., 1998). In its inactive state, the prototypic NF-κB dimer, consisting of subunits p50 and p65 (Rel A), is present in the cytoplasm bound to an inhibitory protein, IκB (Baeuerle & Baltimore, 1988). NF-κB is activated to translocate to the nucleus after degradation of IκB (Traencker et al., 1994) in response to a number of stimuli including inflammatory cytokines (Baeuerle & Henkel, 1994; Marks-Konczalik et al., 1998), pathogenic micro-organisms (Krull et al., 1999; Sharma et al., 1998; Speir et al., 1998) and bacterial LPS (Kol et al., 1999; Pistritto et al., 1999).

Acetyl salicylic acid (aspirin), widely used to treat inflammatory disease, can specifically inhibit the activation of NF-κB through binding to IκB kinase-β (IκBk), an enzyme that phosphorylates IκB, leading to its degradation (Kopp & Ghosh, 1994; Yin et al., 1998). Recent experiments have shown that aspirin inhibits cytochromeP450-induced NF-κB activation and prevents replication of the virus (Speir et al., 1998). In addition, aspirin and another non-steroidal anti-inflammatory drug, indomethacin, inhibit COX-2 activity and synergize in the block the formation of prostaglandins (Gierse et al., 1999).

Recently, it has been demonstrated that C. pneumoniae infection in endothelial cells triggered activation of NF-κB, induced phosphorylation of p42/p44 MAPK and induced the expression of adhesion molecules such as ICAM-1, VCAM-1 and endothelial-leukocyte adhesion molecule-1 (E-Selectin). This was followed by subsequent rolling, adhesion and migration of leukocytes (Krull et al., 1999).

In the present study, we have demonstrated the effect of aspirin on chlamydial growth and activation pathways of NF-κB, COX-2 and prostaglandin E2 (PGE2).

METHODS

Cell culture. HEp-2 cells (ATCC CCL-23), a human epithelioid larynx carcinoma-derived cell line, was maintained in Iscove's modified Dulbecco's medium (IMDM; Gibco-BRL) supplemented with 10% heat-inactivated fetal calf serum (FCS; PAA Laboratories), 100 μg ampicillin mL⁻¹ and 50 μg gentamicin mL⁻¹. Cells pre-cultured at 37°C with 5% CO₂ in 75 or 25 cm² culture flasks (Sumilon) were allowed to adhere to tissue-culture plates (Sumilon) prior to use.

Chlamydial strain. C. pneumoniae strain J318, isolated in Japan in 1994 (Shira et al., 2000), was grown in HEp-2 cells and primary elements (EBs) were purified by discontinuous centrifugation in uracograftin (Caldwell et al., 1981). EBs, diluted with a sucrose/phosphate/glutamate buffer supplemented with 10% FCS, were stored at -80°C until use. Titration was performed and titres were expressed as inclusion-forming units (i.f.u.) mL⁻¹.

Inoculation of C. pneumoniae. The stock chlamydial suspension was thawed and diluted in IMDM. For the growth assay, HEp-2 cells (5×10⁵ per well) grown in IMDM in 96-well tissue-culture plates for 24 h were infected with 3×10⁵ i.f.u. per well, resulting in an m.o.i. of 0·03. For other experiments, cells grown in 24-well plates received 1×10⁶ i.f.u. per well, while cells grown in 6-well plates received 8×10⁴ i.f.u. per well, resulting in an m.o.i. of 0·4 in each case. The inoculum was centrifugated at 700 g for 1 h at 22°C followed by incubation at 36°C for a further hour. After the extracellular bacteria were removed, infected cells were further incubated in IMDM with or without aspirin (acetyl salicylic acid) or indomethacin (1-[p-chlorobenzoyl]-5-methoxy-2-methylindole-3-acetic acid) (Sigma) at the concentrations indicated. The concentrations of drugs used in this study were similar to those used in a previous analysis (Yin et al., 1998). Non-infected cells were treated similarly with the drugs.

NF-κB reporter gene assay. Plasmid pmNFkB-Luc, carrying five NF-κB DNA-binding sites driving the expression of the luciferase gene, and plasmid pCMVβ, carrying the β-galactosidase gene (Siebenlist et al., 1996), were purchased from Stratagene. HEp-2 cells (2×10⁴) grown in 24-well plates for 24 h were co-transfected with 800 ng of the reporter plasmid, pmNFkB-Luc and 60 ng of the control plasmid, pCMVβ using the Trans IT-LT polyamine transfection reagent (Mirus) (Budker et al., 1996; Gupta et al., 1996) followed by incubation for 20 h. The transfected cells were infected with C. pneumoniae at an m.o.i. of 0·4. At the indicated time-points (0, 8, 24 and 48 h), cells were washed with PBS and lysed in 150 μl lysis buffer (Pica Gene). The cell extracts were assayed for luciferase in a luminometer (MicoLumat LB 96P; Berthold) and for β-galactosidase activity after heat-inactivation of endogenous β-galactosidase (Shaper et al., 1994). Relative luciferase activity was defined as the mean ± S.D. (n = 5) of the activity ratio of luciferase/β-gal.

Immunoblot analysis of cyclooxygenase. HEp-2 cells were grown in 6-well plates, infected with C. pneumoniae and then treated with drugs. At the indicated time-points, cells were washed with cold PBS, harvested and lysed in SDS sample buffer (62·5 mM Tris/HCl, pH 6·8, 2% SDS, 10% glycerol, 5% β-mercaptoethanol, 0·1% bromphenol blue). Samples were sonicated three times for 5 s each in a cold-water bath with a sonicator (Bioruptor; Cosmo Bio) and heated to 100°C for 5 min. Samples, containing 20 μg protein, were electrophoresed in 10% SDS-polyacrylamide gels and separated proteins were transferred on to a nitrocellulose membrane. The membrane was blocked for 3 h with 5% non-fat dried milk in Tris-buffered saline with 0·1% Tween 20 at room temperature and incubated overnight at 4°C with rabbit polyclonal IgG anti-COX-2 or anti-COX-1 antibodies (Santa Cruz Biotechnology). The appropriate secondary horseradish peroxidase-conjugated antibody (Amersham Pharmacia Biotech) was added and complexes were detected by enhanced chemiluminescence (Amersham Pharmacia Biotech).

Determination of PGE2. HEp-2 cells were grown in 24-well plates and infected with C. pneumoniae (2×10⁵ i.f.u. per well). At the indicated time-points, PGE2 levels in culture supernatants were measured using a PGE2 ELISA radioimmunoassay (BIOTRA II, Amersham Pharmacia Biotech) as described in the manufacturer’s instruction manual.

Determination of NO. NO (nitrite plus nitrate) was determined using an HPLC NO-detector system (ENOS II; Amersham Pharmacia Biotech) as described previously (Matsushima et al., 1999). Briefly, NO in culture supernatant, after centrifugation at 1000 g for 1 min, was injected into the HPLC-system, consisting of an ion-exchange column to separate nitrite and nitrate and a cadmium-reduction column to reduce nitrate to nitrite. Total nitrite was mixed with Griess reagent and the absorbance at 520 nm was measured using a flow-through spectrophotometer.

Growth of C. pneumoniae. Growth of C. pneumoniae was determined by counting inclusion bodies. After the infection was established, the inoculum was replaced with IMDM with or without aspirin or indomethacin and incubated further for up to 48 h at 36°C. The cells were fixed, stained and examined under a fluorescence microscope at a magnification of ×200 for the presence of inclusion bodies. Immunofluorescence staining of C. pneumoniae was performed with the C. pneumoniae-specific mAb RR402 (Washington Research), as described previously (Matsushima et al., 1999). Numbers of i.f.u. were determined...
RESULTS

Inhibition of *C. pneumoniae*-induced NF-κB activation by aspirin

NF-κB activation in *C. pneumoniae*-infected HEp-2 cells was measured by NF-κB reporter gene assay (Fig. 1). NF-κB activity (indicated as relative luciferase activity) was increased at 8 and 24 h post-infection and decreased to non-infected levels after 48 h. Conversely, TNF-α treatment of the cells (positive control; maximal activation of NF-κB of the treated cells is usually observed after a few hours) showed maximal activation of NF-κB after 8 h without infection but the activity decreased sharply after 24 h and, to a marginal extent, after 48 h. When aspirin (0·1 or 2·0 mM) was added to infected HEp-2 cells, *C. pneumoniae*-induced NF-κB activation was inhibited to non-infected levels.

Induction of COX-2 by *C. pneumoniae* and its inhibition by aspirin

Since NF-κB is one of the controlling factors of COX-2 expression, we then determined COX-2 levels in *C. pneumoniae*-infected HEp-2 cells by immunoblotting (Fig. 2a). Amounts of COX-2 increased from 8 to 48 h after infection in a time-dependent manner compared with the basal level in non-infected cells. On the other hand, levels of the housekeeping COX-1 protein were not affected by chlamydial infection. Addition of aspirin (2 mM) partially decreased *C. pneumoniae*-induced COX-2 expression after 48 h of infection (Fig. 2b), possibly because COX-2 expression is activated by other transcription factors. Indomethacin had no effect on COX-2 expression (Fig. 2b).

PGE₂ is produced in response to *C. pneumoniae* infection

At 8–48 h after *C. pneumoniae* infection, large amounts of PGE₂ were produced in culture supernatants of the HEp-2 culture, peaking at 24 h (Fig. 3). Aspirin and indomethacin, both non-selective COX inhibitors, completely blocked the *C. pneumoniae*-induced production of PGE₂ due to inhibi-
tion of COX-2 activity, although indomethacin inhibits the enzyme activity of COX-2 but not its expression, as shown in Fig. 2(b).

**NO production in HEp-2 cells after C. pneumoniae infection**

Intriguingly, amounts of NO produced by C. pneumoniae-infected HEp-2 cells were essentially the same as those produced by non-infected cells, although HEp-2 cells that received a cytokine mixture containing TNF-α, IL-1β and IFN-γ showed increased NO (Table 1). TNF-α alone had no effect (data not shown). A larger inoculum of C. pneumoniae was toxic to host cells and was not tested for NO production.

**Effects of aspirin on chlamydial growth**

When HEp-2 cells were incubated for 48 h in the presence of aspirin, relative chlamydial growth, determined by the number of inclusion bodies, was 71.2 ± 2.5 % with 1 mM aspirin and 59.7 ± 5.1 % with 2 mM aspirin (Fig. 4a). In contrast, indomethacin did not affect chlamydial growth. A slight increase in chlamydial growth was observed at a low dose (0.1 mM) of aspirin. A high dose (2 mM) of aspirin not only decreased the numbers of inclusion bodies but also inhibited their enlargement (Fig. 4b, c). Thus, the mean diameter of 30 C. pneumoniae inclusion bodies chosen at random was 3.2 ± 0.4 μm in the presence of 2 mM aspirin and 5.4 ± 0.6 μm in its absence (significant difference, P < 0.01). Interestingly, the number of inclusion bodies in aspirin-treated cultures recovered to non-treated levels after incubation for 72 h, but the size of inclusion bodies remained the same (data not shown). The concentrations of aspirin used in these experiments were not toxic to the host cells under the conditions used; cell morphology remained normal and more than 95 % of the cells were viable after the aspirin treatment. However, 50 mM aspirin was cytotoxic to HEp-2 cells.

EBs and HEp-2 cells were treated separately with 2 mM aspirin for 1 or 2 h, respectively, prior to infection. This treatment did not affect the subsequent growth of C. pneumoniae in HEp-2 cells in the presence or absence of 2 mM aspirin (data not shown), suggesting that aspirin inhibits proliferation of C. pneumoniae in host cells following infection.

**Effect of tryptophan on aspirin-inhibited chlamydial growth**

We found that the inhibition of chlamydial growth by high doses of aspirin was reversed by adding tryptophan to the culture medium in a dose-dependent manner; relative chlamydial growth, inhibited by 2 mM aspirin (59.7 ± 5.1 %), was increased to 75.3 ± 7.4 % with 10 μg tryptophan ml⁻¹ and to almost 100 % with 100 μg tryptophan ml⁻¹ (Fig. 5).

**DISCUSSION**

C. pneumoniae infection activates several signal transduction pathways in the host cell that trigger and/or enhance inflammatory reactions, and may act as a causative agent of atherosclerosis. Several studies, including this one, have shown that C. pneumoniae infection increases host-cell NF-kB activity (Krull et al., 1999; Matsushima et al., 1999; Dechend et al., 1999; Molestina et al., 2000). In this study, NF-kB activation was greater at 8 h after infection than at any other time, suggesting that some unknown mechanism(s) might inhibit NF-kB activation during the late phase of chlamydial growth or that C. pneumoniae growing in inclusion bodies does not affect the activation of NF-kB, although the infection might stimulate the activation system. We also demonstrated that aspirin at concentrations as low as 0.1 mM inhibited C. pneumoniae-induced NF-kB activation in HEp-2 cells. Since aspirin, a common anti-inflammatory agent, inhibits IKK-β activity (Yin et al., 1998), we suggest that the activation of NF-kB by C. pneumoniae infection depends mainly on the activation of IKK-β in HEp-2 cells. Another important finding of this study is that C. pneumoniae infection did not induce production of NO in HEp-2 cells, despite NF-kB activation. We reported previously that lymphotixin inhibits C. pneumoniae growth in HEp-2 cells.

### Table 1. NO production by C. pneumoniae-infected and non-infected HEp-2 cells

<table>
<thead>
<tr>
<th>Group</th>
<th>Time post-infection</th>
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<tr>
<td></td>
<td>8 h</td>
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<tr>
<td>Non-infected</td>
<td>9.42 ± 0.08</td>
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<tr>
<td>C. pneumoniae-infected</td>
<td>10.16 ± 0.56</td>
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<tr>
<td>Cytokine mixture added</td>
<td>12.62 ± 0.31*</td>
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*Statistically significantly different versus non-infected controls; P < 0.05.
possibly by NO production (Matsushima et al., 1999). NO has antimicrobial activity and transcription of the IFN-γ gene is regulated by NF-κB and AP-1 (Chu et al., 1998; Marks-Konczalik et al., 1998). It is plausible that C. pneumoniae may have a system to inhibit NO production by host cells so as to aid survival within infected cells.

Expression of COX-2 is induced by LPS (D’Acquisto et al., 1997), growth factors, cytokines and extracellular stimuli under the control of several transcriptional factors such as AP-2, SP-1 and NF-κB (Appleby et al., 1994; Pistritto et al., 1999). In this study, we found that C. pneumoniae-induced COX-2 production in HEp-2 cells, possibly through NF-κB activation, and this expression was partially inhibited by aspirin but not by indomethacin. C. pneumoniae infection enhances PGE2 production, which is completely blocked by aspirin and indomethacin by direct inhibition of COX-2 activity (Gierse et al., 1999). Prostaglandins of the E series, for example PGE2, are produced by the action of COX-2 on arachidonic acid liberated from membrane phospholipids. It has been demonstrated that PGE2 inhibits human T-cell proliferation (Goodwin et al., 1977) and also induces angiogenesis (He & Stuart, 1999). It has also been reported that COX-2 expression is increased in atherosclerotic plaques, predominantly in surrounding areas, in response to C. pneumoniae (Song et al., 2000). Our findings suggest that C. pneumoniae infection is involved in the progression of inflammatory responses through activation of NF-κB, which induces COX-2 and PGE2.

We also found that aspirin at high doses (1 and 2 mM) inhibited the formation of chlamydial inclusion bodies and proliferation of the bacterium within inclusion bodies in HEp-2 cells. These results suggest that the anti-chlamydial activity of aspirin might be associated with the inhibition of host-cell metabolism, including depletion of essential factors during chlamydial growth. Support for this assumption comes from the finding that the inhibition of chlamydial growth by aspirin was overcome when tryptophan was added to the culture medium. There was no significant effect of tryptophan addition alone on chlamydial growth (i.f.u.) in our culture system in the absence of aspirin (not shown).

Tryptophan is an essential amino acid for chlamydiae and proliferation of the bacterium within inclusion bodies in HEp-2 cells. These results suggest that the anti-chlamydial activity of aspirin might be associated with the inhibition of host-cell metabolism, including depletion of essential factors during chlamydial growth. Support for this assumption comes from the finding that the inhibition of chlamydial growth by aspirin was overcome when tryptophan was added to the culture medium. There was no significant effect of tryptophan addition alone on chlamydial growth (i.f.u.) in our culture system in the absence of aspirin (not shown). Tryptophan is an essential amino acid for chlamydiae and reduction of its availability might disturb various metabolic processes, depressing intracellular growth of the pathogen (Pantoja et al., 2000). It has been demonstrated recently that IFN-γ restricts the growth of C. pneumoniae in HEp-2 cells through induction of the tryptophan-catabolizing enzyme indoleamine 2,3-dioxygenase, and the number of typical inclusion bodies decreased with an increase in smaller, less-dense, atypical inclusion bodies containing large, reticulate-like aberrant bodies (Pantoja et al., 2001). Further studies, including ultrastructural morphology of inclusion bodies and indoleamine 2,3-dioxygenase activity in aspirin-treated cells, should be carried out to determine whether the aspirin- and IFN-γ-induced inhibition of C. pneumoniae growth is mediated through a common mechanism. It also remains to be clarified whether the inhibition of NF-κB pathways in the presence of aspirin is related to tryptophan catabolism and

### Table 1: Effect of tryptophan on inhibition of chlamydial growth by aspirin

<table>
<thead>
<tr>
<th>Aspirin (mM)</th>
<th>Tryptophan (µg ml⁻¹)</th>
<th>Relative chlamydial growth (%)</th>
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<tr>
<td>0</td>
<td>0</td>
<td>120</td>
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<tr>
<td>0</td>
<td>10</td>
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<td>0</td>
<td>40</td>
<td>40</td>
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<tr>
<td>0</td>
<td>50</td>
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Statistical significance of differences: *, P < 0.05; **, P < 0.01.

### Figure 4: Effects of aspirin and indomethacin on chlamydial growth in HEp-2 cells

(a) Cells grown in 96-well plates were infected with C. pneumoniae and incubated with (filled bars) or without (open bar) aspirin or indomethacin. Staining was performed with mAb RR402. Relative chlamydial growth (%) of infected cells from drug-treated samples (filled bars) is expressed as means ± SD of five separate experiments. Statistical significance: *, P < 0.05; **, P < 0.01 (versus non-treated control). (b)–(c) Immunofluorescence staining of C. pneumoniae J138 inclusion bodies in the absence (b) or presence (c) of 2 mM aspirin. HEp-2 cells were infected and incubated for 48 h. Bars, 10 µm.

### Figure 5: Effect of tryptophan on inhibition of chlamydial growth by aspirin.

HEp-2 cells infected with C. pneumoniae were incubated with 2 mM aspirin in the absence or presence of 10 or 100 µg tryptophan ml⁻¹ in the culture medium. Data are presented as means ± SD of five separate experiments. Statistical significance of differences: *, P < 0.01; **, P < 0.05.
whether other mechanisms of tryptophan depletion, independent of NF-κB pathways, are responsible for the attenuation of chlamydial growth. Very similar results describing the effect of aspirin on chlamydial growth and NF-κB activation by C. pneumoniae were published after our initial submission to the journal (Tiran et al., 2002). However, they did not demonstrate rescue from growth inhibition by tryptophan or investigate activation of COX-1 and -2 and PGEl in response to infection by C. pneumoniae, all of which were demonstrated in this study. Our results suggest that C. pneumoniae, a possible pathogen involved in atherosclerosis, might trigger and/or enhance inflammatory reactions in atherosclerosis through NF-κB activation and they raise the possibility that aspirin therapy might be useful for C. pneumoniae infection in atherosclerosis, in addition to chemotherapy.

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