0022-3565/06/3181-389–394$20.00
THE JOURNAL OF PHARMACOLOGY AND EXPERIMENTAL THERAPEUTICS
JPET 318:389–394, 2006

Vol. 318, No. 1
102251/3122649
Printed in U.S.A.

Nuclear Factor-κB-Independent Anti-Inflammatory Action of Salicylate in Human Endothelial Cells: Induction of Heme Oxygenase-1 by the c-Jun N-Terminal Kinase/Activator Protein-1 Pathway

Robert Fürst, Signe B. Blumenthal, Alexandra K. Kiemer, Stefan Zahler, and Angelika M. Vollmar

Department of Pharmacy, Pharmaceutical Biology, University of Munich, Munich, Germany (R.F., S.B.B., S.Z., A.M.V.); and Institute of Pharmaceutical Biology, Saarland University, Saarbrücken, Germany (A.K.K.)

Received February 3, 2006; accepted April 18, 2006

ABSTRACT

In contrast to aspirin, salicylate, its active metabolite, possesses profound anti-inflammatory properties without blocking cyclooxygenase. Inhibition of the transcription factor nuclear factor-κB (NF-κB) has been discussed to play a role in the anti-inflammatory profile of salicylate. However, NF-κB-independent effects of salicylate have been assumed but have up to now been poorly investigated. Therefore, the aim of the present study was to investigate NF-κB-independent anti-inflammatory mechanisms of salicylate in human umbilical vein endothelial cells using interleukin-4 (IL-4) as NF-κB-independent proinflammatory stimulus and P-selectin as inflammatory read-out parameter. Using quantitative real-time reverse transcription-polymerase chain reaction, we found that salicylate decreases IL-4-induced P-selectin expression. As judged by Western blot analysis, salicylate increased endothelial heme oxygenase-1 (HO-1) protein levels. Using both the HO-1 inhibitor tin(II) protoporphyrin IX and HO-1 antisense oligonucleotides, we causally linked the induction of HO-1 to the decrease of P-selectin. Moreover, we were interested in the signaling mechanisms leading to the up-regulation of HO-1 by salicylate. c-Jun NH_2-terminal kinase (JNK) was found to be activated by salicylate, and we could causally link this activation to the induction of HO-1 by using the JNK inhibitor 1,9-pyrazoloanthrone. By applying activator protein-1 (AP-1) decoys, it was shown that the transcription factor AP-1 is crucially involved in the up-regulation of HO-1 downstream of JNK. In summary, our study introduces HO-1 as novel NF-κB-independent anti-inflammatory target of salicylate in human endothelial cells. Moreover, we elucidated the JNK/AP-1 pathway as crucial for the induction of HO-1 by salicylate.

Aspirin—acetyl salicylic acid—is the most widely used drug in the world because it possesses profound analgesic, anti-thrombotic, and anti-inflammatory properties (Vane and Botting, 2003). For many years, these properties have been ascribed to the ability of aspirin to block prostaglandin synthesis by inhibition of cyclooxygenase (COX) (Vane and Botting, 2003). However, several lines of evidence point to COX-independent anti-inflammatory effects: The doses of aspirin needed to medicate chronic inflammatory disorders are much higher than those required to inhibit prostaglandin synthesis. Salicylate, the active metabolite of aspirin, rather than the rapidly deacetylated aspirin is considered to exert anti-inflammatory effects and does not inhibit COX (Tegeder et al., 2001). In fact, salicylate is known to impair the activation of the transcription factor NF-κB (Kopp and Ghosh, 1994), which plays a crucial role in the regulation of many proinflammatory genes. Nevertheless, the inhibition of NF-κB was not proven to be of importance for the anti-inflammatory effects of salicylate in vivo (Cronstein et al., 1999). Therefore, NF-κB-independent effects of salicylate have been assumed but have as yet been poorly investigated.

The endothelium is an important regulator of inflammatory events because it plays a crucial role in the attraction, adhesion, and migration of leukocytes to sites of inflammation (Biedermann, 2001). Due to this important role for endothelial cells in inflammatory events, we aimed to investi-

Article, publication date, and citation information can be found at http://jpet.aspetjournals.org.
doi:10.1124/jpet.106.102251.

ABBREVIATIONS: COX, cyclooxygenase; NF-κB, nuclear factor-κB; IL-4, interleukin-4; HO-1, heme oxygenase-1; AP-1, activator protein-1; HUVEC, human umbilical vein endothelial cell(s); TNF-α, tumor necrosis factor-α; SnPP, tin(II) protoporphyrin IX; NaSal, sodium salicylate; SP600125, 1,9-pyrazoloanthrone; PCR, polymerase chain reaction; JNK, c-Jun N-terminal kinase; EMSA, electrophoretic mobility shift assay; MAPK, mitogen-activated protein kinase; RT, reverse transcription.

gate NF-κB-independent effects of salicylate in human endothelial cells. We chose interleukin-4 (IL-4) as the proinflammatory stimulus. IL-4 is an immunomodulatory cytokine secreted by activated T cells, eosinophils, and mast cells, and it plays an important role in the pathology of chronic inflammatory disorders such as asthma (Bradding et al., 1992) or atherosclerosis (Sasaguri et al., 1998). Moreover, IL-4 is known to induce genes that are generally associated with an activated, proinflammatory status of the endothelium, such as P-selectin (Yao et al., 1996). We chose this molecule as inflammatory read-out parameter to analyze the effects of salicylate on the IL-4-induced, NF-κB-independent activation of human endothelial cells.

Heme oxygenase-1 (HO-1) is the rate-limiting enzyme in heme degradation. It catalyzes the cleavage of heme to yield free iron, carbon monoxide, and biliverdin. HO-1 has increasingly been recognized to possess a wide range of biological effects because it is tightly involved in both physiological as well as pathophysiological processes, such as atherogenesis (Ishikawa and Maruyama, 2001) and ischemia-reperfusion injury (Tsuchihashi et al., 2004). Recently, there has been accumulating evidence that HO-1 possesses profound anti-inflammatory features (Alcaraz et al., 2003). Because the transcription factor AP-1 has been shown by ourselves to induce HO-1 expression in endothelial cells (Kiemer et al., 2003) and aspirin in principle is able to increase AP-1 activity (Vartiainen et al., 2003), we hypothesized that salicylate could exert its anti-inflammatory properties via induction of HO-1.

Thus, the aim of the present study was to investigate an NF-κB-independent anti-inflammatory mechanism of salicylate in primary human umbilical vein endothelial cells (HUVEC) using IL-4 as proinflammatory stimulus and P-selectin as inflammatory read-out parameter. We hypothesized that salicylate is able to induce HO-1 and that this induction is able to attenuate the IL-4-evoked increase of P-selectin. Moreover, we sought to clarify the underlying signaling pathways by which HO-1 is induced by salicylate.

Materials and Methods

Materials. Human recombinant IL-4 and TNF-α were from Sigma-Aldrich (Taufkirchen, Germany). The HO-1 inhibitor tin(II) protoporphyrin IX (SnPP) (for reference, see Drummond and Kappas, 1981) was from Alexis (Grünberg, Germany), and sodium salicylate (NaSal) was from Fluka (Buchs, Switzerland). The JNK inhibitor 1,9-pyrazoloanthrone (SP600125) (for reference, see Bennett et al., 2001) was from Calbiochem (Schwalbach, Germany). Mouse monoclonal anti-human HO-1 antibody (clone 23) was from BD Biosciences (Heidelberg, Germany). Mouse monoclonal anti-human phospho-JNK (Thr183/Tyr185) antibody (clone G9) and horseradish peroxidase-conjugated goat anti-mouse antibody were from Cell Signaling/New England Biolabs (Frankfurt/Main, Germany). Primers for P-selectin and GAPDH were from Invitrogen (Karlsruhe, Germany). TaqMan probes for P-selectin and GAPDH were from Applied Biosystems (Hamburg, Germany).

Cell Culture. HUVEC were prepared by digestion of umbilical veins as described previously (Kiemer et al., 2002a). Cells were cultured in endothelial cell growth medium (Promocell, Heidelberg, Germany) supplemented with 10% heat-inactivated fetal calf serum (Biochrom, Berlin, Germany) and used for all experiments at passage 3. Cells were routinely tested for mycoplasma contamination with the PCR detection kit VenorGeM (Minerva Biolabs, Berlin, Germany).

Measurement of P-Selectin mRNA Levels by Quantitative Real-Time Reverse Transcription-Polymerase Chain Reaction. Cells were grown in six-well plates until confluence and treated as indicated in the respective figure legends. Extraction of total mRNA was performed with the RNeasy Mini Kit (Qiagen, Hilden, Germany). RNase-free DNase was applied for DNase digestion (RNase-free DNase Set; Qiagen). Reverse transcription was carried out using the RNA PCR Core Reagent Kit (Applied Biosystems, Hamburg, Germany) in a GeneAmp PCR system 9700 (Applied Biosystems). Real-time PCR was performed using the TaqMan PCR Core Reagent Kit (Applied Biosystems) in a GeneAmp 5700 Sequence Detection System (Applied Biosystems). P-selectin forward primer: 5′-TGAAGGAAGGTTTTCTCCACTTTG-3′; reverse primer: 5′-AGACTCCAGAAGATGCTACAGGAATT-3′; probe: 5′-TGGAAAGCAGGTGGCATCTCTAATTGGA-3′. GAPDH forward primer: 5′-GGGAAGGTGAAGGTCGGAGT-3′; reverse primer: 5′-TCCACTTTACCAGAGTTAAAAGCAG-3′; probe: 5′-ACCAGGCGCCCAATACGACCAA-3′. Results were quantified based on the relative expression of the P-selectin gene versus the housekeeping gene GAPDH using the mathematical model for relative quantification according to Pfaffl (2001).

Measurement of HO-1 and Phospho-JNK Protein Expression by Western Blot Analysis. Cells were grown in six-well plates until confluence and were treated as indicated in the respective figure legends. Western blot analysis was performed as described previously (Kiemer et al., 2002a). HO-1 antibody and phospho-JNK antibody (see *Materials*) were diluted 1:250 and 1:1000, respectively. For densitometric analysis, the Kodak 1D software version 3.5.4 (Eastman Kodak, Rochester, NY) was used.

Measurement of NF-κB and AP-1 DNA-Binding Activity by Electrophoretic Mobility Shift Assay. Cells were grown in six-well plates until confluence and were treated as indicated in the respective figure legends. Nuclear extracts were prepared, and electrophoretic mobility shift assay (EMSA) was performed as described previously (Kiemer et al., 2002b). Consensus binding sequence for AP-1 is 5′-CGCTTGATGAGTCAGCCGGAA-3′ (Promega, Mannheim, Germany) and for NF-κB is 5′-AGTTGAGGGGACTTTCCCAGGC-3′ (Promega). For densitometric analysis, the OptiQuant software version 4.00 (PerkinElmer Life and Analytical Sciences, Boston, MA) was used.

HO-1 Antisense and AP-1 Decoy Experiments. Cells were grown in six-well plates until 80% confluence and were transfected with HO-1 antisense phosphorothioate oligonucleotides (antisense: 5′-CGCCTTCATGGTGCC-3′; sense: 5′-GGCACCATGAAGGCG-3′) according to Wagener et al. (1999) or AP-1 decoy phosphorothioate oligonucleotides (decoy: 5′-CGCTTGATGACTCAGCCGGAA-3′; scrambled decoy: 5′-CGCTTGATGACTTGGCCGGAA-3′) according to Jan et al. (2000) by using the jetPEI-RGD transfection reagent (Polyplus-Transfections/Biomol, Hamburg, Germany). Cells were treated for 4 h with the DNA-jetPEI-RGD complexes. Experiments were performed 24 h (HO-1 antisense) or 3 h (AP-1 decoy) after transfection.

Statistical Analysis. Unless stated otherwise, all experiments were done from at least three different cell preparations in at least duplicates. Data are expressed as mean ± S.E.M. Statistical analysis was performed with the GraphPad Prism software version 3.03 (GraphPad Software Inc., San Diego, CA). To compare three or more groups, one-way analysis of variance followed by Newman-Keuls post hoc test was used.

Results

IL-4 Does Not Influence NF-κB DNA-Binding Activity. To confirm the lack of NF-κB activation for our experimental setting, we treated HUVEC with IL-4 and analyzed NF-κB DNA-binding activity. TNF-α, a well known activator of NF-κB, served as a positive control: TNF-α dramatically increased NF-κB activity (Fig. 1A). However, IL-4 did not alter NF-κB DNA-binding activity at any time point (Fig.

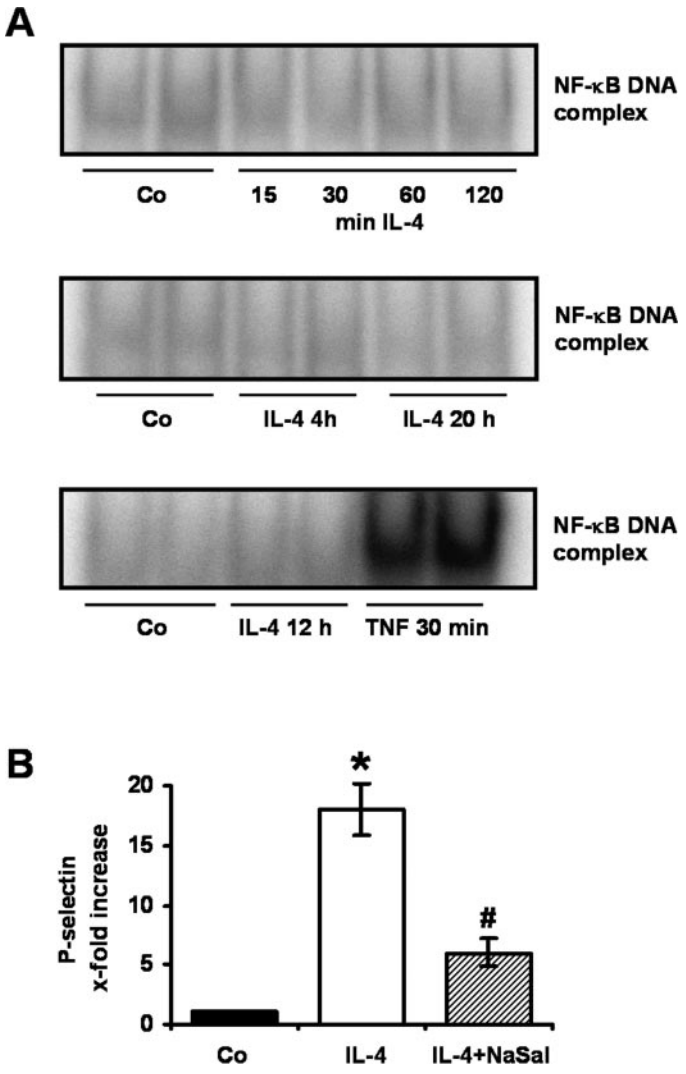

Fig. 1. A, IL-4 does not influence NF-κB DNA-binding activity. Cells were either left untreated (Co) or were treated with IL-4 (10 ng/ml) for the indicated times. Treatment with TNF-α (10 ng/ml, 30 min) served as positive control. NF-κB DNA-binding activity was analyzed by EMSA as described under *Materials and Methods*. B, the induction of P-selectin by IL-4 is reduced by NaSal. Cells were either left untreated (Co) or were treated with IL-4 (10 ng/ml) for 20 h with or without pretreatment with NaSal (10 mM) for 60 min. Levels of P-selectin mRNA were determined by quantitative real-time RT-PCR as described under *Materials and Methods*. *, $p < 0.001$ compared with Co. #, $p < 0.001$ compared with IL-4.

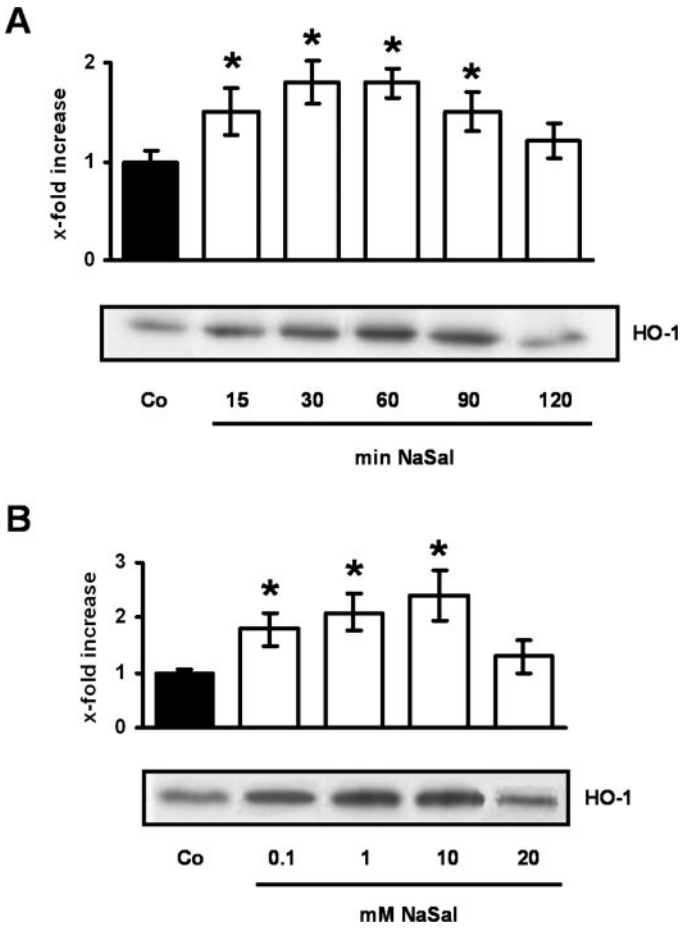

Fig. 2. Induction of HO-1 protein expression by NaSal. A, cells were either left untreated (Co) or were treated with NaSal (10 mM) for the indicated times. B, cells were either left untreated (Co) or were treated with the indicated concentration of NaSal for 60 min. HO-1 protein levels were determined by Western blot analysis as described under *Materials and Methods*. *, $p < 0.01$ compared with Co.

1A). This finding confirms that IL-4 does not activate NF-κB in human endothelial cells.

The IL-4-Evoked Increase of P-Selectin Is Reduced by NaSal. P-selectin, a product of a gene involved in endothelial inflammation, is known to be induced by IL-4 in HUVEC. We confirmed this in our experimental setting (Fig. 1B). Pretreatment with sodium salicylate (NaSal, 10 mM) strongly reduced the expression of P-selectin (Fig. 1B).

NaSal Induces Endothelial HO-1. Because we hypothesized that HO-1 could be responsible for the observed NF-κB-independent actions of NaSal, we first investigated whether NaSal is able to induce HO-1 protein expression in primary human endothelial cells. In fact, treatment with NaSal led to an increase of HO-1 protein expression with maximal protein levels at approximately 60 min (Fig. 2A) and 10 mM (Fig. 2B).

HO-1 Is Involved in the Decrease of IL-4-Induced P-Selectin by NaSal. Because we observed an up-regulation of HO-1 by NaSal, we assumed that HO-1 might be involved in the decrease of IL-4-induced P-selectin expression by NaSal. We treated HUVEC with the HO-1 blocker SnPP and found that the NaSal-evoked inhibition of P-selectin expression was clearly diminished (~50% reversal) (Fig. 3A). Moreover, we performed HO-1 antisense experiments and revealed that an attenuated induction of HO-1 protein expression due to the presence of antisense oligonucleotides leads to a diminished reduction of P-selectin levels (~30% reversal) (Fig. 3B). Control experiments confirmed that the used HO-1 antisense oligonucleotides are in fact able to attenuate endothelial HO-1 protein levels (Fig. 3C). Our findings suggest an involvement of NaSal-induced HO-1 in the decrease of IL-4-evoked P-selectin expression.

NaSal Induces HO-1 Protein Expression via JNK. We aimed to elucidate the underlying signaling mechanism by which salicylate leads to an up-regulation of endothelial HO-1 protein levels. We hypothesized that MAPK could be involved. Indeed, as shown by the detection of the phosphorylated form of the MAPK JNK (phospho-p54/JNK2 and phospho-p46/JNK1), NaSal activated JNK after 15 min. The amount of phosphorylated JNK returned to almost basal

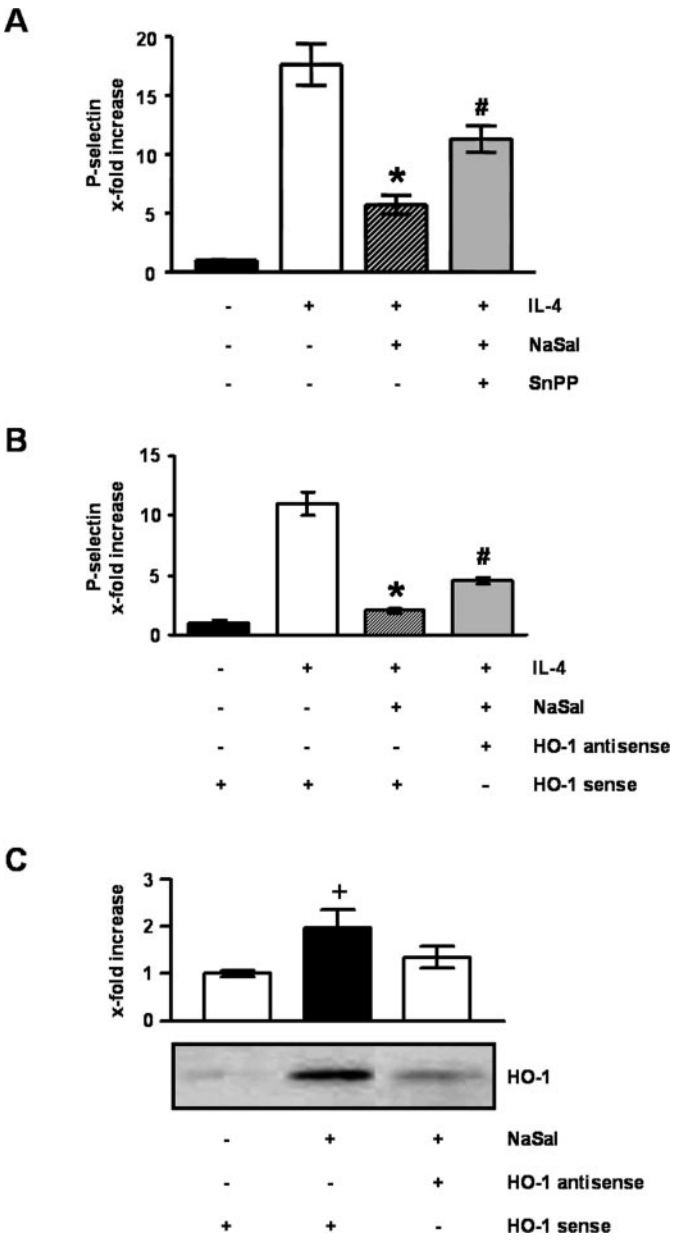

Fig. 3. A, the HO-1 inhibitor SnPP reduces the NaSal-evoked decrease of IL-4-induced P-selectin expression. Cells were either left untreated or were treated with IL-4 (10 ng/ml) for 20 h with or without pretreatment with NaSal (10 mM) for 60 min. SnPP (10 μM) was applied 30 min before NaSal. Levels of P-selectin mRNA were determined by quantitative real time RT-PCR as described under *Materials and Methods*. B, silencing of HO-1 reduces the NaSal-evoked decrease of IL-4-induced P-selectin expression. Cells were either left untreated or were treated with NaSal (10 mM) for 60 min in the presence of HO-1 antisense or sense oligonucleotides. Levels of P-selectin mRNA were determined by quantitative real time RT-PCR as described under *Materials and Methods*. C, functionality of the HO-1 antisense approach. Cells were either left untreated or were treated with NaSal (10 mM) for 60 min in the presence of HO-1 antisense or sense oligonucleotides. HO-1 protein levels were determined by Western blot analysis as described under *Materials and Methods*. Antisense experiments were performed as described under *Materials and Methods*. *, $p < 0.001$ compared with the IL-4/IL-4 + HO-1 sense group. #, $p < 0.001$ compared with the IL-4 + NaSal + SnPP/HO-1 antisense group. +, $p < 0.05$ compared with the only HO-1 sense-treated group.

levels after 60 min (Fig. 4A). Activation of JNK was found to be crucial for the up-regulation of HO-1 because the pharmacological JNK inhibitor SP600125 abrogated the NaSal-induced increase of HO-1 protein levels (Fig. 4B). These findings point to an involvement of JNK in the mechanism by which NaSal induces HO-1.

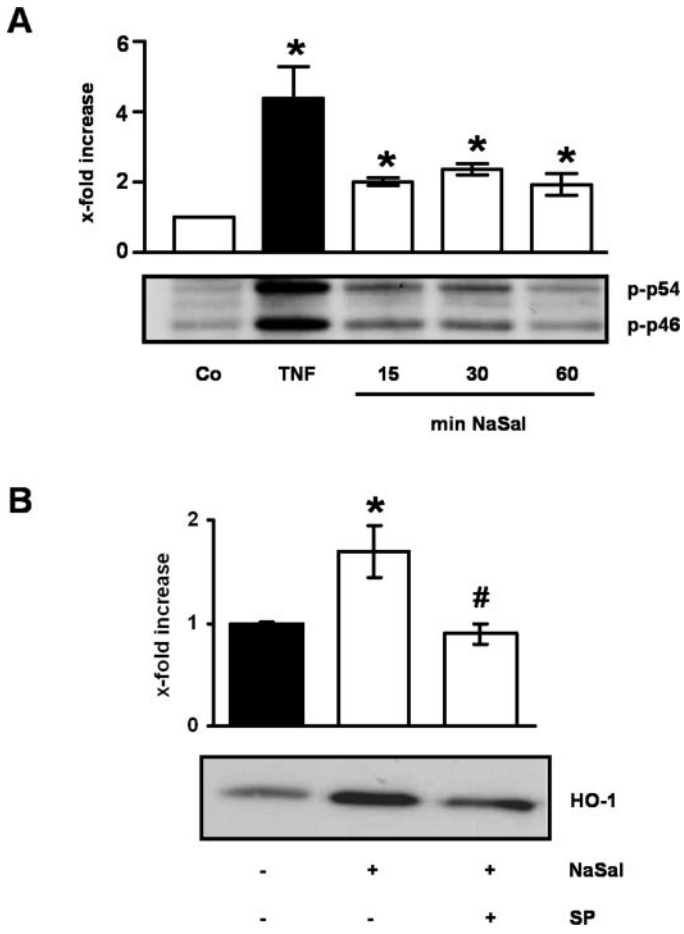

Fig. 4. A, NaSal activates JNK. Cells were either left untreated (Co) or were treated with NaSal (10 mM) for the indicated times. TNF-α (10 ng/ml, 30 min) served as positive control. B, JNK is crucially involved in the induction of HO-1 by NaSal. Cells were either left untreated or were treated with NaSal (10 mM) for 60 min. The JNK inhibitor SP600125 (SP, 10 μM) was added 60 min before NaSal. Phospho-JNK and HO-1 protein levels were determined by Western blot analysis as described under *Materials and Methods*. *, $p < 0.01$ compared with the untreated group. #, $p < 0.001$ compared with NaSal.

NaSal Induces HO-1 Protein Expression via AP-1. Downstream of JNK, we wanted to clarify whether the transcription factor AP-1 might be involved in the induction of HO-1 by NaSal. In fact, treatment of HUVEC with NaSal led to strong time-dependent activation of AP-1 DNA-binding activity (Fig. 5A). Furthermore, transfection of HUVEC with AP-1 decoys completely blocked the ability of NaSal to induce HO-1 (Fig. 5B), suggesting that AP-1 activation is crucial for the salicylate-induced increase of HO-1 protein expression.

Discussion

Salicylate possesses profound anti-inflammatory effects, but it does not inhibit COX (Tegeder et al., 2001). Therefore, COX-independent pathways have been postulated. Most attention has been paid to a salicylate-evoked inhibition of the proinflammatory transcription factor NF-κB (Kopp and Ghosh, 1994), although an influence of salicylate on other signal transduction systems commonly associated with inflammatory events, like the MAPK pathway (Pillinger et al.,

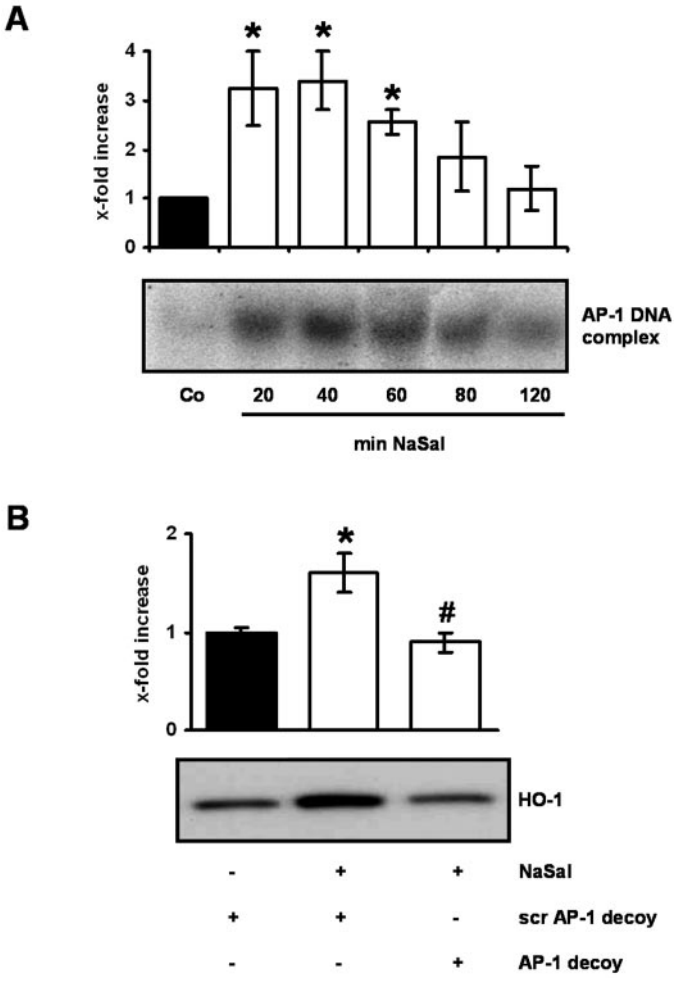

Fig. 5. A, NaSal activates AP-1. Cells were either left untreated (Co) or were treated with NaSal (10 mM) for the indicated times. AP-1 DNA-binding activity was assessed by EMSA as described under *Materials and Methods*. B, AP-1 is crucially involved in the induction of HO-1 by NaSal. Cells were either left untreated or were treated with NaSal (10 mM) for 60 min in the presence of AP-1 decoys or scrambled (scr) decoys. Decoy experiments were performed as described under *Materials and Methods*. HO-1 protein levels were determined by Western blot analysis as described under *Materials and Methods*. *, $p < 0.01$ compared with Co. #, $p < 0.001$ compared with the NaSal + scr AP-1 decoy group.

1998), the AP-1 pathway (Dong et al., 1997), and the nuclear factor of activated T cell pathway (Aceves et al., 2004) have also been shown to contribute to the anti-inflammatory profile of salicylate. In the present work, we provide for the first time evidence that HO-1 is a further NF-κB-independent player in the complex concert of anti-inflammatory mechanisms evoked by salicylate.

For the following reasons, we applied sodium salicylate at high concentrations (10 mM): according to Amann and Peskar (2002), anti-inflammatory therapy with aspirin (which rapidly deacetylates to its active metabolite salicylate) results in plasma salicylate concentrations of approximately 2 mM. Moreover, salicylate is known to accumulate in inflamed tissue (Brune, 1977). Unfortunately, no data exist about the precise concentrations of salicylates in inflamed tissue, but it seems obvious that high concentrations of salicylate—as used in our in vitro model—are required to mimic the in vivo situation of an effective anti-inflammatory action. To investigate potential cytoxic effects evoked by 10 mM salicylate, we performed CellTiter Blue cell viability assays (Promega) and, thus, excluded remarkable cytotoxicity at this concentration (data not shown).

Aiming to identify NF-κB-independent mechanisms, we used IL-4 as proinflammatory stimulus and confirmed that no influence on NF-κB was exerted by IL-4. This is in accordance with data from other groups showing no alteration of NF-κB activity upon treatment of endothelial cells with IL-4 (McCarty et al., 1995; Xia et al., 1998). Importantly, salicylate was found to block the IL-4-induced increase of the used read-out parameter for endothelial inflammation, P-selectin. Inhibition of P-selectin by salicylate has previously been observed (Xia et al., 1998) and was confirmed in our experimental setting.

In terms of the salicylate-evoked inhibition of P-selectin expression, we show for the first time that salicylate is able to induce HO-1 protein expression in primary human endothelial cells and that the observed HO-1 induction is a feature linked to the inhibition of P-selectin by salicylate. However, it should be kept in mind that neither the HO-1 inhibitor nor the HO-1 antisense approach completely reversed the effect of salicylate. Although additional NF-κB-independent anti-inflammatory pathways targeted by salicylate have to be discussed in the context of our data, our study introduces HO-1 as a novel NF-κB-independent molecular target of salicylate in endothelial inflammatory processes. This finding is in line with many studies that link HO-1 to anti-inflammatory features (Wagener et al., 2003) and is strengthened by observations made in the case of HO-1 deficiency (Yachie et al., 1999). Two recently published studies (Grosser et al., 2003; Nascimento-Silva et al., 2005) showing the ability of aspirin to induce HO-1 in ECV304 also support our data.

Based on the novel role for salicylate-induced HO-1 in the endothelium, the underlying signaling mechanisms were of interest. We could show that salicylate increases HO-1 protein expression in human endothelial cells via activation of JNK and the transcription factor AP-1. Experiments using a pharmacological JNK inhibitor (SP600125) (Bennett et al., 2001) and inhibiting DNA binding of AP-1 by decoy oligonucleotides (Jan et al., 2000) in fact indicate a crucial role for the JNK/AP-1 pathway in the signaling events responsible for the up-regulation of HO-1. In support of our findings, JNK activation by salicylate has also been observed in human eosinophils (Wong et al., 2000), HO-29 colon cancer (Schwenger et al., 1999), and COS-1 cells (Schwenger et al., 1999). Interestingly, salicylate inhibits an already activated JNK in fibroblasts and mouse epidermal cells (Huang et al., 1997; Schwenger et al., 1997), suggesting that the effects of salicylate on JNK activity highly depend both on the cellular context and on the activity status of JNK in the current experimental setting. Our results are also supported by the finding that the human HO-1 gene contains AP-1 binding sites (Lavrovsky et al., 1994) and by corresponding data for some other stimuli of HO-1 induction (Terry et al., 1998; Kiemer et al., 2003). However, our finding that salicylate induces DNA binding of AP-1 differs from most of the published data, which describe an inhibitory effect of salicylates on AP-1. In mouse epidermal cells, aspirin and salicylate have been shown to inhibit epidermal growth factor-induced AP-1 activation and basal AP-1 levels (Dong et al., 1997). In addition, in human cell systems, salicylates have shown inhibitory action on AP-1, for instance, in human cervical can-

cer cells (Murono et al., 2000). All this seems to be in contrast to our findings. However, all these opposing studies show inhibitory effects of salicylates only in settings where the cells have already been activated by diverse stimuli. Publications reporting basal stimulatory effects on the JNK/AP-1 pathway are rare (Schwenger et al., 1999; Wong et al., 2000; Vartiainen et al., 2003), and none are available for the human endothelium. Thus, to the best of our knowledge, this is the first report proving that activation of the JNK/AP-1 signaling pathway is crucial for the salicylate-induced HO-1 expression in the human endothelium.

Due to this involvement of the JNK/AP-1 pathway, the question raises how salicylate is able to activate JNK. Interestingly, salicylate has recently been described to evoke oxidative stress (Battaglia et al., 2005), which could account for the activation of JNK that represents a classic stress-activated protein kinase (Adler et al., 1999). To test this hypothesis, we measured the generation of reactive oxygen species as described previously (Fürst et al., 2005). However, we could not detect an increase in reactive oxygen species formation upon salicylate treatment (data not shown). We can only speculate that salicylate might activate a kinase upstream of JNK or inhibit a MAPK phosphatase.

In summary, the present study identifies HO-1 as an NF-κB-independent mediator in the anti-inflammatory signaling concert triggered by salicylate in primary human endothelial cells. Thereby, the JNK/AP-1 pathway is crucially involved in the up-regulation of endothelial HO-1. The data add further evidence to the fact that salicylate causes anti-inflammatory effects independent of COX activity and, moreover, not related to NF-κB inhibition.

Acknowledgments

The excellent technical assistance of Cornelia Niemann, Johanna Stöckl, and Ursula Kollmannsberger is gratefully acknowledged. We thank Nicole Barth for help in PCR experiments.

References

Aceves M, Duenas A, Gomez C, San Vicente E, Crespo MS, and Garcia-Rodriguez C (2004) A new pharmacological effect of salicylates: inhibition of NFAT-dependent transcription. *J Immunol* **173:**5721–5729.
Adler V, Yin Z, Tew KD, and Ronai Z (1999) Role of redox potential and reactive oxygen species in stress signaling. *Oncogene* **18:**6104–6111.
Alcaraz MJ, Fernandez P, and Guillen MI (2003) Anti-inflammatory actions of the heme oxygenase-1 pathway. *Curr Pharm Des* **9:**2541–2551.
Amann R and Peskar BA (2002) Anti-inflammatory effects of aspirin and sodium salicylate. *Eur J Pharmacol* **447:**1–9.
Battaglia V, Salvi M, and Toninello A (2005) Oxidative stress is responsible for mitochondrial permeability transition induction by salicylate in liver mitochondria. *J Biol Chem* **280:**33864–33872.
Bennett BL, Sasaki DT, Murray BW, O'Leary EC, Sakata ST, Xu W, Leisten JC, Motiwala A, Pierce S, Satoh Y, et al. (2001) SP600125, an anthrapyrazolone inhibitor of Jun N-terminal kinase. *Proc Natl Acad Sci USA* **98:**13681–13686.
Biedermann BC (2001) Vascular endothelium: checkpoint for inflammation and immunity. *News Physiol Sci* **16:**84–88.
Bradding P, Feather IH, Howarth PH, Mueller R, Roberts JA, Britten K, Bews JP, Hunt TC, Okayama Y, and Heusser CH (1992) Interleukin 4 is localized to and released by human mast cells. *J Exp Med* **176:**1381–1386.
Brune K (1977) Biodistribution of salicylates: a clue to the understanding of some effects and side effects. *Agents Actions Suppl* **2:**163–177.
Cronstein BN, Montesinos MC, and Weissmann G (1999) Salicylates and sulfasalazine, but not glucocorticoids, inhibit leukocyte accumulation by an adenosine-dependent mechanism that is independent of inhibition of prostaglandin synthesis and p105 of NFkappaB. *Proc Natl Acad Sci USA* **96:**6377–6381.
Dong Z, Huang C, Brown RE, and Ma WY (1997) Inhibition of activator protein 1 activity and neoplastic transformation by aspirin. *J Biol Chem* **272:**9962–9970.
Drummond GS and Kappas A (1981) Prevention of neonatal hyperbilirubinemia by tin protoporphyrin IX, a potent competitive inhibitor of heme oxidation. *Proc Natl Acad Sci USA* **78:**6466–6470.
Fürst R, Brueckl C, Kuebler WM, Zahler S, Krötz F, Görlach A, Vollmar AM, and Kiemer AK (2005) Atrial natriuretic peptide induces mitogen-activated protein kinase phosphatase-1 in human endothelial cells via Rac1 and NAD(P)H oxidase/Nox2-activation. *Circ Res* **96:**43–53.
Grosser N, Abate A, Oberle S, Vreman HJ, Dennery PA, Becker JC, Pohle T, Seidman DS, and Schroder H (2003) Heme oxygenase-1 induction may explain the antioxidant profile of aspirin. *Biochem Biophys Res Commun* **308:**956–960.
Huang C, Ma WY, Hanenberger D, Cleary MP, Bowden GT, and Dong Z (1997) Inhibition of ultraviolet B-induced activator protein-1 (AP-1) activity by aspirin in AP-1-luciferase transgenic mice. *J Biol Chem* **272:**26325–26331.
Ishikawa K and Maruyama Y (2001) Heme oxygenase as an intrinsic defense system in vascular wall: implication against atherogenesis. *J Atheroscler Thromb* **8:**63–70.
Jan JT, Chen BH, Ma SH, Liu CI, Tsai HP, Wu HC, Jiang SY, Yang KD, and Shaio MF (2000) Potential dengue virus-triggered apoptotic pathway in human neuroblastoma cells: arachidonic acid, superoxide anion and NF-kappaB are sequentially involved. *J Virol* **74:**8680–8691.
Kiemer AK, Bildner N, Weber NC, and Vollmar AM (2003) Characterization of heme oxygenase 1 (heat shock protein 32) induction by atrial natriuretic peptide in human endothelial cells. *Endocrinology* **144:**802–812.
Kiemer AK, Weber NC, Fürst R, Bildner N, Kulhanek-Heinze S, and Vollmar AM (2002a) Inhibition of p38 MAPK activation via induction of MKP-1: atrial natriuretic peptide reduces TNF-α-induced actin polymerization and endothelial permeability. *Circ Res* **90:**874–881.
Kiemer AK, Weber NC, and Vollmar AM (2002b) Induction of IκB: atrial natriuretic peptide as a regulator of the NF-κB pathway. *Biochem Biophys Res Commun* **295:**1068–1076.
Kopp E and Ghosh S (1994) Inhibition of NF-kappa B by sodium salicylate and aspirin. *Science (Wash DC)* **265:**956–959.
Lavrovsky Y, Schwartzman ML, Levere RD, Kappas A, and Abraham NG (1994) Identification of binding sites for transcription factors NF-kappa B and AP-2 in the promoter region of the human heme oxygenase 1 gene. *Proc Natl Acad Sci USA* **91:**5987–5991.
McCarty JM, Yee EK, Deisher TA, Harlan JM, and Kaushansky K (1995) Interleukin-4 induces endothelial vascular cell adhesion molecule-1 (VCAM-1) by an NF-kappa b-independent mechanism. *FEBS Lett* **372:**194–198.
Murono S, Yoshizaki T, Sato H, Takeshita H, Furukawa M, and Pagano JS (2000) Aspirin inhibits tumor cell invasiveness induced by Epstein-Barr virus latent membrane protein 1 through suppression of matrix metalloproteinase-9 expression. *Cancer Res* **60:**2555–2561.
Nascimento-Silva V, Arruda MA, Barja-Fidalgo C, Villela CG, and Fierro IM (2005) Novel lipid mediator aspirin-triggered lipoxin A4 induces heme oxygenase-1 in endothelial cells. *Am J Physiol* **289:**C557–C563.
Pfaffl MW (2001) A new mathematical model for relative quantification in real-time RT-PCR. *Nucleic Acids Res* **29:**e45.
Pillinger MH, Capodici C, Rosenthal P, Kheterpal N, Hanft S, Philips MR, and Weissmann G (1998) Modes of action of aspirin-like drugs: salicylates inhibit erk activation and integrin-dependent neutrophil adhesion. *Proc Natl Acad Sci USA* **95:**14540–14545.
Sasaguri T, Arima N, Tanimoto A, Shimajiri S, Hamada T, and Sasaguri Y (1998) A role for interleukin 4 in production of matrix metalloproteinase 1 by human aortic smooth muscle cells. *Atherosclerosis* **138:**247–253.
Schwenger P, Alpert D, Skolnik EY, and Vilcek J (1999) Cell-type-specific activation of c-Jun N-terminal kinase by salicylates. *J Cell Physiol* **179:**109–114.
Schwenger P, Bellosta P, Vietor I, Basilico C, Skolnik EY, and Vilcek J (1997) Sodium salicylate induces apoptosis via p38 mitogen-activated protein kinase but inhibits tumor necrosis factor-induced c-Jun N-terminal kinase/stress-activated protein kinase activation. *Proc Natl Acad Sci USA* **94:**2869–2873.
Tegeder I, Pfeilschifter J, and Geisslinger G (2001) Cyclooxygenase-independent actions of cyclooxygenase inhibitors. *FASEB J* **15:**2057–2072.
Terry CM, Clikeman JA, Hoidal JR, and Callahan KS (1998) Effect of tumor necrosis factor-α and interleukin-1α on heme oxygenase-1 expression in human endothelial cells. *Am J Physiol* **274:**H883–H891.
Tsuchihashi S, Fondevila C, and Kupiec-Weglinski JW (2004) Heme oxygenase system in ischemia and reperfusion injury. *Ann Transplant* **9:**84–87.
Vane JR and Botting RM (2003) The mechanism of action of aspirin. *Thromb Res* **110:**255–258.
Vartiainen N, Goldsteins G, Keksa-Goldsteine V, Chan PH, and Koistinaho J (2003) Aspirin inhibits p44/42 mitogen-activated protein kinase and is protective against hypoxia/reoxygenation neuronal damage. *Stroke* **34:**752–757.
Wagener FA, da Silva JL, Farley T, de WT, Kappas A, and Abraham NG (1999) Differential effects of heme oxygenase isoforms on heme mediation of endothelial intracellular adhesion molecule 1 expression. *J Pharmacol Exp Ther* **291:**416–423.
Wagener FA, Volk HD, Willis D, Abraham NG, Soares MP, Adema GJ, and Figdor CG (2003) Different faces of the heme-heme oxygenase system in inflammation. *Pharmacol Rev* **55:**551–571.
Wong CK, Zhang JP, Lam CW, Ho CY, and Hjelm NM (2000) Sodium salicylate-induced apoptosis of human peripheral blood eosinophils is independent of the activation of c-Jun N-terminal kinase and p38 mitogen-activated protein kinase. *Int Arch Allergy Immunol* **121:**44–52.
Xia L, Pan J, Yao L, and McEver RP (1998) A proteasome inhibitor, an antioxidant, or a salicylate, but not a glucocorticoid, blocks constitutive and cytokine-inducible expression of P-selectin in human endothelial cells. *Blood* **91:**1625–1632.
Yachie A, Niida Y, Wada T, Igarashi N, Kaneda H, Toma T, Ohta K, Kasahara Y, and Koizumi S (1999) Oxidative stress causes enhanced endothelial cell injury in human heme oxygenase-1 deficiency. *J Clin Investig* **103:**129–135.
Yao L, Pan J, Setiadi H, Patel KD, and McEver RP (1996) Interleukin 4 or oncostatin M induces a prolonged increase in P-selectin mRNA and protein in human endothelial cells. *J Exp Med* **184:**81–92.

Address correspondence to: Dr. Robert Fürst, Department of Pharmacy, Pharmaceutical Biology, University of Munich, Butenandtstr. 5-13, 81377 Munich, Germany. E-mail: robert.fuerst@cup.uni-muenchen.de