Effects of Novel Anti-Inflammatory Compounds on Healing of Acetic Acid-Induced Gastric Ulcer in Rats

Parke-Davis Pharmaceutical Research Division, Warner-Lambert Co., Ann Arbor, Michigan
Accepted for publication May 8, 1998  This paper is available online at http://www.jpet.org

ABSTRACT
Nonsteroidal anti-inflammatory drugs often cause development of significant GI lesions. Selective inhibitors of prostaglandin G/H synthase/cyclooxygenase-2 (PGHS-2) enzyme and some dual inhibitors of PGHS-5-lipoxygenase (5-LO) enzymes have been reported to be potent anti-inflammatory compounds that carry a much lower risk of having GI irritating effects. We have evaluated the anti-inflammatory effect and the GI safety profile of three new anti-inflammatory compounds: the selective PGHS-2 inhibitors NS-398 and PD 138387 and the PGHS/5-LO dual inhibitor PD 137968. All the compounds tested showed an anti-inflammatory activity in the carrageenan footpad edema test in rats. None of these compounds caused either gastric damage 4 h after p.o. administration of 100 mg/kg in rats or inhibition of PGE_2 synthesis in the stomach. However, when administered p.o. at an effective anti-inflammatory dose to rats with pre-existing acetic acid-induced gastric ulcer, NS-398 caused a statistically significant delay of ulcer healing. No impairment of the ulcer healing was observed with the other compounds evaluated. Derivatives of 2,6-di-tert-butylphenol, whose members may act as PGHS-1/PGHS-2 inhibitors, selective PGHS-2 inhibitors or PGHS/5-LO dual inhibitors, are novel anti-inflammatory compounds that are devoid of GI irritating effects and do not affect the rate of pre-existing gastric ulcer healing.

The use of anti-inflammatory compounds such as NSAIDs is often associated with development of GI side effects such as gastric erosions and ulcer, which often limit their widespread clinical use (Wright, 1995; Jones and Tait, 1995; Henry, 1988).

The anti-inflammatory mechanism of NSAIDs is due mainly to inhibition of PGHS (Smith, 1992; Vane, 1971), an enzyme that catalyzes the conversion of arachidonic acid to PGH_2, which is then further metabolized to various prostaglandins, prostacyclin and thromboxane A_2 (Vane and Botting, 1996; Smith, 1992; Vane, 1971). PGHS exists in a constitutive form (PGHS-1) and in an inducible form (PGHS-2) (Smith, 1992). PGHS-1 is constitutively expressed in almost any tissue, including GI tract (Simmons et al., 1991), whereas expression of PGHS-2 is induced by inflammatory stimuli and growth factors (Smith, 1992; Simmons et al., 1991).

It has been hypothesized that the anti-inflammatory action of NSAIDs is due to inhibition of PGHS-2, whereas the toxic effects on the stomach are due to inhibition of PGHS-1 (Vane, 1994). By this hypothesis, selective inhibitors of PGHS-2 should retain their full anti-inflammatory effect and be associated with much lower toxic effects in the GI tract and stomach. Structural differences between PGHS-1 and PGHS-2 (Jones et al., 1993) have made it possible to design selective PGHS-2 inhibitors (Masferrer et al., 1994). For instance, NS-398 is a selective inhibitor of PGHS-2 that shows a potent anti-inflammatory effect associated with a low risk of significant gastric damage (Futaki et al., 1994; Futaki et al., 1993; Arai et al., 1993). On the other hand, PGHS-1 inhibitors and inhibitors of both PGHS-1/PGHS-2 are much more likely to cause significant gastric lesions (Wallace, 1997; Meade et al., 1993; Michell et al., 1993).

Dual inhibitors are compounds that, in addition to inhibiting PGSH enzyme, also inhibit 5-LO, another major enzyme involved in the metabolism of arachidonic acid. 5-LO is responsible, among other things, for the synthesis of leukotrienes (Smith, 1992), which are also believed to contribute to inflammation and the side effects of NSAIDs (Vaananen et al., 1992; Brain and Williams 1990; Guslandi, 1987). Therefore, dual inhibitors might also be efficacious anti-inflammatory drugs with a better GI safety profile than conventional NSAIDs (Unangst et al., 1994). The development of novel GI-safe anti-inflammatory compounds such as PGHS-2 and dual inhibitors could be a major breakthrough in the treatment of inflammatory conditions such as arthritis. However,
an important issue, which is of clinical relevance, is the effect of new anti-inflammatory drugs on healing of pre-existing gastric ulcer. In this study, therefore, we examined the effect of new anti-inflammatory compounds on inhibition of PGHS-1, PGHS-2 and 5-LO and their effect on healing of pre-existing acetic acid-induced gastric ulcers in rats.

### Materials and Methods

**Compounds.** NS-398, PD137968 (hydrochloride salt) and PD 138387 (choline salt) were all synthesized at Parke-Davis Pharmaceutical Research Division. Indomethacin and bacterial LPS were purchased from Sigma (St. Louis, MO). Immediately before their use, all the compounds were suspended in 1% CMC (Sigma) followed by 10-sec sonication.

**Inhibition of isolated PGHS isoforms.** Inhibitory potencies were determined against purified recombinant human PGHS-2 (rhPGHS-2) isolated from baculovirus-infected Sf9 cells and against commercially obtained ram seminal vesicle PGHS-1 (oPGHS-1, Cayman Chemical, Ann Arbor, MI). Inhibition assays were conducted in 50 mM phosphate buffer, pH 7.5, containing 2 mM epinephrine as cofactor for the PGHS peroxidase reaction and 20 μM [14C]-arachidonic acid as substrate. rhPGHS-2 or oPGHS-1, in phosphate buffer containing Tween-20, was added in sufficient amount to convert 20% to 30% of added substrate to products in a 1-min incubation. Reaction products were separated from unconverted substrate and measured by radiometric HPLC analysis. Inhibition was measured as the percentage reduction of product formation compared with that in inhibitor-free incubations, and the concentration of compound causing 50% inhibition (IC₅₀) was estimated with the software package KaleidaGraph, version 3.0.1 (Synergy Software Reading, PA) on a Macintosh Centris 650 (Apple Computers, Cupertino, CA) running System 7.1.

**Whole-Blood thromboxane synthesis.** Male (Crl:CD(SD)BR) rats were treated p.o. with the following compounds and doses: NS-398, 2 mg/kg; PD 137968, 11.4 mg/kg; PD 138387, 38 mg/kg. Indomethacin was used as a positive control and was administered p.o. at a dose of 2.5 mg/kg. All compounds were administered in a volume of 1 ml. Control animals received the same volume of vehicle (1% CMC) p.o. Three hours after administration of the compounds, animal were lightly anesthetized, and blood was drawn by cardiac puncture. After a 45-min incubation in a water bath at 37°C, blood samples were centrifuged at 2000 × g for 10 min, and 1 ml of serum was removed and its TXB₂ concentration measured with a commercially available ELISA kit (Assays Designs). Because platelets are the predominant source of thromboxane synthesis and contain only the PGHS-1 isoform (Xie et al., 1992; Meade et al., 1993), this assay served as an index of inhibitory effects of the test drug on PGHS-1 activity.

**Whole-blood LPS-stimulated PGE₂ synthesis.** Rats were treated p.o. with the following compounds and doses: NS-398, 2 mg/kg; PD 137968, 11.4 mg/kg; PD 138387, 38 mg/kg. Indomethacin was used as a positive control and was administered p.o. at a dose of 2.5 mg/kg. All compounds were administered in a volume of 1 ml. Control animals received the same volume of vehicle (1% CMC) p.o. After 30 min, animals were injected i.p. with 1 ml of a 5 mg/kg solution of LPS. Three hours from the time the animals were administered the compounds under study, and under light ether anesthesia, blood was drawn by cardiac puncture and incubated in a water bath at 37°C for 45 min. The blood samples were then centrifuged at 2000 × g for 10 min, and 1 ml of serum was removed and used for PGE₂ measurement with a commercially available ELISA kit (Assays Designs). Because LPS administered p.o. induces a diffuse inflammatory response with expression of the PGHS-2 isoform and consequent stimulation of PGHS products such as PGE₂, this assay was used as a positive control and was administered p.o. at a dose of 2.5 mg/kg. All compounds were administered in a volume of 1 ml. Control animals received the same volume of vehicle (1% CMC) p.o. After 30 min, animals were injected i.p. with 1 ml of a 5 mg/kg solution of LPS. Three hours from the time the animals were administered the compounds under study, and under light ether anesthesia, blood was drawn by cardiac puncture and incubated in a water bath at 37°C for 45 min. The blood samples were then centrifuged at 2000 × g for 10 min, and 1 ml of serum was removed and used for PGE₂ measurement with a commercially available ELISA kit (Assays Designs). Because LPS administered p.o. induces a diffuse inflammatory response with expression of the PGHS-2 isoform and consequent stimulation of PGHS products such as PGE₂, this assay served as an index of inhibitory effects of the test drug on PGHS-2 activity.
based computer equipped with CUE3 system imaging analysis software (Olympus Corp., Marietta, GA). Two 6-mm biopsies were taken from a constant region located in each side of the glandular portion of the stomach, and their PGE2 content was measured with a commercially available ELISA kit (Assay Designs). The presence of gastric damage was determined with the retrieved electronic image, and the extent measured was determined with the CUE3 imaging software. Data were expressed as ulcer index, which was obtained by multiplying the percent frequency of the gastric damage by the extent of the damage.

**Induction of gastric ulcer.** After a 24-h food fast, male (Crl: CD(SD)BR) rats were anesthetized with an i.m. injection of a ketamine/xylazine mix. Under sterile conditions, the abdomen of the animals was opened, the stomach exposed and 20 μl of 100% acetic acid was injected into the gastric wall near the antral portion of the stomach using a Hamilton syringe with a 30-gauge needle. Control animals received no surgical modifications. The abdomen was then sutured, and the animals were allowed to recover and returned to their cages with food and water ad libitum. Injection of 20 μl of acetic acid causes the development of a single deep ulceration, which, after reaching its maximum size, starts to heal. The healing process starts around day 3 and is completed in about 4 weeks (Baragi et al., 1997).

To evaluate the relationship between development of acetic acid gastric ulcer and gastric content of prostaglandins, we sacrificed the animals at weeks 2, 3 and 4. The stomach was removed, opened along the greater curvature, rinsed in saline and pinned out on a flat surface. Inflammatory doses used throughout the study, act as selective PGHS-2 inhibitors, and are effective anti-inflammatory compounds on the healing process and to avoid any interference with the formation phase of acetic acid ulcer, the compounds measured their PGE2 content with a commercially available ELISA kit (Assay Designs). In order to study the effect of the anti-inflammatory compounds on the healing process and to avoid any interference with the formation phase of acetic acid ulcer, the compounds used in this study were administered 3 days after injection of acetic acid. For each compound, an effective anti-inflammatory dose equal to twice the ED40 on CFE was used. NS-398 was administered at a dose of 2.0 mg/kg, PD 137968 at a dose of 11.4 mg/kg and PD 138387 at a dose of 38 mg/kg. This treatment regimen was repeated daily for the duration of the study.

**Measurement of ulcer area.** Groups of animals were sacrificed at weeks 2, 3 and 4. The stomach was removed, opened along the greater curvature, rinsed in saline and pinned out on a flat surface. The image of the stomach was then digitized with CUE3 image analysis software (Olympus Corp.) installed on a 486-based computer equipped with a color camera and stored on a magneto-optical disk. Measurement of the ulcer crater was performed on the retrieved image. Briefly, the edges of the ulcer crater were traced, and the area of the ulcer was automatically calculated by the computer and expressed in square millimeters.

**Statistics.** Data on CFE were analyzed by paired t test, and the results were considered significant at a level of P < .05. All the other data were analyzed by Kruskal-Wallis one-way ANOVA followed by Dunnett's test. Results were considered significant at a level of P < .05.

**Results**

**In vitro inhibition of isolated PGHS-1 and PGHS-2.** The IC50 values of the compounds evaluated in this study against isolated isoforms of PGHS and 5-LO are reported in table 1. NS-398 behaved as a selective PGHS-2 inhibitor with weak inhibitory activity against PGHS-1 isoform and no significant inhibitory activity against 5-LO. PD 138387 behaved as a dual inhibitor of 5-LO and PGHS-2 with no activity against PGHS-1. PD 137968, on the other hand, inhibited PGHS-1 and PGHS-2 equally well (although 50% inhibition was not reached) and had more potent inhibitory activity against 5-LO. As expected, indomethacin inhibited both PGHS-1 and PGHS-2 but failed to produce any significant inhibition of 5-LO.

**Inhibition of PGHS-1 or PGHS-2 in platelets or J774A.1 cells.** The selectivity of NS-398 and PD 138387 for the PGHS-2 isoform was confirmed by measuring the inhibitory activity of these compounds on the PGHS-1 and PGHS-2 enzymes present in human platelets and J774A.1 cells, respectively. In these cell-based assays, in addition to the potent inhibitory effect against PGHS-2, NS-398 also displayed a less potent inhibitory activity against PGHS-1, whereas PD 138387 was unable to cause a 50% inhibition against the same enzyme at the highest concentration tested (20 μM). PD 137968, on the other hand, potently inhibited the PGHS-1 enzyme in platelets but had no effect on the PGHS-2 isoform in J774A.1 cells. Indomethacin was able to inhibit PGHS-1 and PGHS-2 enzymes equally well.

**Effect of CFE.** All the compounds used in this study showed an anti-inflammatory effect in the CFE test and reduced the swelling of the paw caused by injection of carrageenan (fig. 1). The order of potency of the compounds tested, based on the ID40, was NS-398 > PD 137968 > PD 138387.

**Effect of indomethacin, NS-398, PD 137968 and PD 138387 on in vivo inhibition of PGHS-1 and PGHS-2.** Oral administration of 2 mg/kg NS-398, 11.4 mg/kg PD 137968 and 38 mg/kg PD 138387 significantly inhibited LPS-stimulated PGE2 synthesis but did not significantly affect the synthesis of TxB2 in serum (fig. 2). Because the former assay serves as an indicator of PGHS-2 inhibition, whereas the latter indicates inhibitory activity against PGHS-1, our results suggest that these compounds, at the effective anti-inflammatory doses used throughout the study, act as selective PGHS-2 inhibitors in vivo. As expected, when a known inhibitor of both PGHS-1 and PGHS-2, such as indomethacin, was used in the same study, significant inhibitory synthesis of both TxB2 (PGHS-1-dependent) and PGE2 (PGHS-2-dependent) was observed (fig. 2).

**Development of gastric damage and the effect on PGE2 synthesis in the stomach.** Four hours after administration of 100 mg/kg NS-398, PD 137968 and PD 138387, animals did not show any macroscopic gastric damage (ulcer index = 0). Conversely, animal treated with the same dose of indomethacin had diffuse areas of gastric damage (ulcer index = 13.36) (table 2). Indomethacin strongly inhibited the synthesis of PGE2 in the stomach. Much weaker inhibition or
no inhibition of PGE2 synthesis was observed with NS-398, PD 137968 and PD 138387 (table 2).

**Effect on healing of acetic acid gastric ulcer and on PGE2 synthesis in the stomach.** Development of acetic acid gastric ulcer was associated with an elevation of PGE2 in the area of ulceration but not in nonulcerated gastric areas (fig. 3). To assess the effects on the healing rate of acetic acid ulcer, daily p.o. treatment with the novel anti-inflammatory compounds under study was initiated at day 3 after administration of acetic acid, when the healing phase had already started. Rats treated with PD 137968 or PD 138387 showed a healing rate comparable to that of vehicle-treated control animals. On the other hand, treatment with NS-398 significantly slowed the healing process (fig. 4). At week 4, animals treated with NS-398 had an average crater size of 9.56 ± 1.56 mm2 compared with 1.79 ± 0.49 mm2 for control animals.

**Discussion**

Development of efficacious anti-inflammatory drugs devoid of gastric irritating effects would represent a major breakthrough in the treatment of chronic inflammatory conditions such as arthritis. In this regard, PGHS-2 inhibitors seem to be promising agents that combine a potent anti-inflammatory activity with a low risk of inducing significant gastric side effects. In addition, compounds that inhibit both PGHS and 5-LO may also represent anti-inflammatory compounds with a better GI safety profile than NSAIDs.

When tested on isolated enzymes, all the compounds evaluated in this study behaved as either selective inhibitors of PGHS-2 (NS-398) or inhibitors of 5-LO and of either both isoforms of the PGHS enzyme (PD137968) or PGHS-2 alone (PD 138387) (table 1). Cell-based assays largely confirmed the selectivity of NS-398 and PD 138387 for PGHS-2, whereas, contrary to what was observed on the isolated enzyme assay, PD 137968 showed a more potent activity against PGHS-1 (table 3). These differences can be explained by the more complex environment of a whole-cell assay. Be-
cause in vitro inhibition of PGHS-1 and PGHS-1 is not always indicative of in vivo inhibition, we also evaluated the selectivity of NS-398, PD 137968 and PD 138387 for the PGHS-2 isoform by measuring the effect of these compounds, at the effective anti-inflammatory dose used throughout this study, on TxB₂ and LPS-stimulated PGE₂ levels in serum after p.o. administration of the compounds. All compounds that we tested significantly inhibited LPS-induced PGE₂ synthesis but not TxB₂ synthesis, which suggests that also in vivo, at the doses used in this study, these compounds act as selective PGHS-2 inhibitors. Interestingly, PD 137968 showed a better selectivity for PGHS-2 in vivo than in vitro. On the other hand (and as expected), indomethacin in the same assays inhibited TxB₂ and LPS-stimulated PGE₂ equally well, which confirms the ability of this compound to inhibit both PGHS-1 and PGHS-2.

In results compatible with their in vitro and in vivo activity against the PGHS-2 isoform, all the compounds tested in this study showed an anti-inflammatory effect on the CFE assay (fig. 1). The selective PGHS-2 compound NS-398 showed the most potent anti-inflammatory activity, followed by the PGHS/5-LO inhibitor PD137968. A somewhat weaker anti-inflammatory activity was observed with the other selective PGHS-2 inhibitor tested, PD 138387, despite the fact that this compound also showed some inhibitory activity against 5-LO in vitro (table 1). This may be explained by its weaker PGHS-2-inhibitory activity compared with NS-398, which is not compensated by its weaker inhibitory activity on 5-LO. When administered to rats, none of the compounds tested except indomethacin caused gastric damage, even at doses seven-fold above those required for an anti-inflammatory effect (table 2). The development of gastric toxicity of anti-inflammatory compounds has been correlated to their ability to inhibit PG synthesis in the stomach. It is consistent with this relationship that NS-398, PD 137968 and PD 138387 did not significantly inhibit PGE₂ synthesis. On the other hand, as expected, significant inhibition of PGE₂ synthesis was observed with the damaging agent indomethacin.

The compounds we tested differed widely in their ability to interfere with the healing of pre-existing ulcers. The PGHS-2 inhibitor NS-398 significantly delayed the healing of acetic acid-induced ulcer. After 4 weeks of treatment, healing of the acetic acid-induced ulcers in control animals was almost complete, whereas animals treated with NS-398 still had large ulcerations in their stomachs. None of the other compounds tested in this study affected the healing of acetic acid-induced ulcers, and rats treated with the compounds showed a healing rate similar to that of control animals.

It is unclear at the present time whether the impairment of healing rate observed with NS-398 is a consequence of the selective inhibition of PGHS-2, or a characteristic of the chemical structure of NS-398. Mizuno et al. (1997) also reported that NS-398 i.p. administered at a dose of 1 mg/100 g in mice also impairs healing of acetic acid-induced gastric ulcer, and the moderate selective PGHS-2 inhibitor nabumetone was reported to exacerbate the TNBS-induced colonic damage in rats (Reuter et al., 1996). These data suggest that PGHS-2 inhibition might be responsible for the impairment of ulcer healing throughout the GI tract. However, this hypothesis is weakened by the observation that in our study, no delay of healing rate was observed with PD 138387, a selective PGHS-2 inhibitor that belongs to a different chemical class than NS-398. However, PD138387 is also a 5-LO inhibitor. Therefore, it is possible that inhibition of 5-LO activity somehow counteracts the impairment of ulcer healing caused by PGHS-2 inhibitors. Interestingly, inhibition of gastric ulcer healing and exacerbation of TNBS-induced colonic damage have also been reported with another PGHS-2 inhibitor, namely L-745,337 (Schmassmann et al., 1996), which belongs to the same chemical class as NS-398.

Taken together, these data suggest that N-substituted methanesulfonamides PGHS-2 inhibitors (such as NS-398 and L-745,337) might be responsible for the impairment of GI ulcer healing. On the other hand, PD 138,387, in addition to selectively inhibiting PGHS-2, also has some inhibitory activity on 5-LO, and no impairment of ulcer healing was observed with the PGHS/5-LO inhibitor PD 137,968. This raises the possibility that, independently of the chemical

![Fig. 4. Effect of NS-398, PD 137968 and PD 138387 on healing of acetic acid-induced gastric ulcer in rats. Compounds were administered daily at using an effective anti-inflammatory dose equal to twice the ED₅₀ on CFE. Treatment was started 3 days after induction of acetic acid gastric ulcer. Ulcer crater size was measured weekly. * P < .05 based on one-way ANOVA followed by Dunnett’s test and compared with vehicle-treated group. N = 7 to 12 animals per group.](image-url)

TABLE 3

<table>
<thead>
<tr>
<th>Compound</th>
<th>n</th>
<th>PGHS-1 IC₅₀</th>
<th></th>
<th>n</th>
<th>PGHS-2 IC₅₀</th>
<th>J774A.1 IC₅₀</th>
<th>PGHS-1/PGHS-2 IC₅₀ Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS 398</td>
<td>16</td>
<td>3.3 μM ± 0.73</td>
<td>12</td>
<td>0.022 μM ± 0.0077</td>
<td></td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>PD 137968</td>
<td>3</td>
<td>1.7 μM ± 0.21</td>
<td>3</td>
<td>NC</td>
<td>&lt;0.0085</td>
<td></td>
<td>&gt;91</td>
</tr>
<tr>
<td>PD 138387</td>
<td>3</td>
<td>NC</td>
<td>4</td>
<td>0.22 μM ± 0.095</td>
<td></td>
<td>&gt;91</td>
<td></td>
</tr>
<tr>
<td>Indomethacin</td>
<td>20</td>
<td>0.008 μM ± 0.00075</td>
<td>12</td>
<td>0.005 μM ± 0.0012</td>
<td></td>
<td>&gt;1.6</td>
<td></td>
</tr>
</tbody>
</table>

n = number of experiments. IC₅₀ represents the average value of n experiments ± S.E. NC means inhibitory activity did not reach 50% inhibition at the highest concentration tested (20 μM), and IC₅₀ could not be calculated.
structure, inhibition of PGHS-2 may delay ulcer healing if 5-LO activity remains undisturbed.

The impairment of ulcer healing with NS-398 was observed at an effective anti-inflammatory dose (twice the ID50 on CFE), so a decrease in the rate of ulcer healing is likely to be observed during treatment of inflammatory processes with this drug at the dose used in this study. Therefore, this effect may be of clinical importance, especially in the case of patients affected by chronic inflammatory conditions who were previously treated with NSAIDs or other ulcerogenic compounds. On the other hand, because a dose of 2 mg/kg of NS-398 produces a near-maximum anti-inflammatory effect on CFE, it is possible that certain mild inflammatory processes may be treated with lower anti-inflammatory doses of the drug, at which the impairment of the ulcer healing may not occur.

In conclusion, our data suggest that the impairment of the healing process observed with NS-398 may be a characteristic of PGHS-2 inhibitors belonging to the same chemical class and that it is not necessarily shared by other PGHS-2 inhibitors. Concurrent inhibition of 5-LO may also play an important role. On the other hand, derivatives of the 2,6-di-tert-butylphenol class are potent anti-inflammatory compounds that are devoid of gastric irritating effects and do not cause any delay of healing of pre-existing gastric ulcers.

References


