Role of cyclooxygenase-2 in Helicobacter pylori-induced gastritis in Mongolian gerbils

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Takahashi, Satoru, Takuya Fujita, and Akira Yamamoto. Role of cyclooxygenase-2 in Helicobacter pylori-induced gastritis in Mongolian gerbils. Am J Physiol Gastrointest Liver Physiol 279: G791–G798, 2000.—Cyclooxygenase (COX)-2 expression is induced in the gastric mucosa of Helicobacter pylori-infected patients, but its role remains unclear. We examined the effects of NS-398 and indomethacin on gastritis and COX-2 expression in Mongolian gerbils. COX-1 was detected in both normal and H. pylori-infected mucosa, whereas COX-2 was expressed only in the infected mucosa. PGE2 production was elevated by H. pylori infection, and the increased production was reduced by NS-398, which did not affect PGE2 production in normal mucosa. Indomethacin inhibited PGE2 production in both normal and infected mucosa. Hemorrhagic erosions, neutrophil infiltration, lymphoid follicles, and epithelium damage were induced by H. pylori infection. NS-398 and indomethacin aggravated these pathological changes but did not increase viable H. pylori number. H. pylori-increased production of neutrophil chemokine and interferon-γ was potentiated by NS-398 and indomethacin. Neither NS-398 nor indomethacin caused any pathological changes or cytokine production in normal animals. These results indicate that COX-2 as well as COX-1 might play anti-inflammatory roles in H. pylori-induced gastritis.

of nonsteroidal anti-inflammatory drugs (NSAIDs) (38). COX exists in two isoforms, of which COX-1 is constitutively expressed in many tissues, including the stomach, and COX-2 is normally undetectable in most tissues, its expression being induced at inflammatory sites (13, 23). In the normal gastric mucosa, COX-1-derived PGs play a crucial role in maintaining mucosal integrity (14, 18). In contrast, COX-2 is not expressed in normal mucosa, but its induction results in a marked and sustained increase in PGE2 production in the damaged mucosa (24, 32, 37). In addition to COX-1, COX-2 also plays an important role in the healing of gastric ulcers (24, 32). Recent studies showed that COX-2 expression is observed in the gastric mucosa of H. pylori-positive patients (22, 31, 33). In addition, Romano et al. (29) reported that H. pylori directly induces COX-2 mRNA expression and increases PGE2 production in gastric cancer MKN28 cells. However, the role of COX-2 in H. pylori-induced gastritis in vivo remains unclear.

Mongolian gerbil models of H. pylori infection have been established and widely used (15, 16, 20, 21, 34). We have shown that chronic gastritis and ulcers are generated in all H. pylori-infected animals (20, 34). In addition, Watanabe et al. (41) recently reported that gastric cancers are also developed by H. pylori infection in gerbils. Thus the gerbil model is quite suitable for in vivo study of the pathogenesis of H. pylori-induced gastric diseases, since this model exhibits pathological features that mimic those of human patients with H. pylori.

To investigate the role of COX-2 in H. pylori-induced gastritis, we examined the effect of NS-398, a COX-2-selective inhibitor, on H. pylori-induced pathological changes in Mongolian gerbils, compared with indomethacin, a nonselective COX inhibitor.

METHODS

Animals. Male Mongolian gerbils (6 wk old, 40–50 g) were kindly supplied from Nihon SLC (Hamamatsu, Japan). The animals were kept in an isolated clean room with regulated temperature (20–22°C) and humidity (~55%) with a 12:12-h light/dark cycle. The animals were fasted for 24 h before H.
pylori inoculation, and drinking water was also withheld after the inoculation. From 4 h after the inoculation, both food and water were freely available to the animals.

**H. pylori preparation and inoculation of Mongolian gerbils.** The preparation and inoculation of H. pylori were performed as we previously described (34). A caqA- and vacA-positive standard strain of H. pylori (NCTC 11637; American Type Culture Collection, Rockville, MD) was used. The bacteria were incubated in a brain-heart infusion broth (Difco Laboratories, Detroit, MI) containing 10% fetal bovine serum (GIBCO BRL, Gaithersburg, MD) at 37°C overnight under a microaerophilic atmosphere and allowed to grow to a density of $2.0 \times 10^{8}$ colony-forming units (CFU)/mL. H. pylori (2.0 $\times \ 10^{8}$ CFU; 1.0 ml) was orally administered to each animal. Normal animals received 1.0 ml of the medium alone.

**Western blot analysis of COX-1 and COX-2 proteins.** Expression of COX-1 and COX-2 proteins in the gastric mucosa was examined by Western blotting. Gastric specimens (the fundus near the antrum) were taken from normal and H. pylori-infected animals. COX proteins were partially purified according to the method of Giese et al. (26). The specimens were homogenized in 25 mM Tris-HCl (pH 8.0) buffer containing 250 mM sucrose, followed by centrifugation at 10,000 g for 20 min. The pellet was resuspended in 25 mM Tris-HCl (pH 8.0) buffer containing 1% 3-[[(3-cholamidopropyl)dimethylammonio]-1-propanesulfonate, and the mixture was gently stirred for 2 h at 4°C. The supernatant was recovered after centrifugation at 10,000 g for 20 min. The amounts of CINC/KC, IFN-$\gamma$, and IL-10 productions were determined by enzyme immunoassay (CINC/KC EIA kit; Immuno Star; Wako Pure Chemicals, Osaka, Japan).

**Determination of PGE$_2$ production.** Gastric specimens (the fundus near the antrum) were taken from normal and H. pylori-infected animals. After being washed with PBS, the tissues were minced and then incubated in 1 ml of Dulbecco’s modified Eagle’s medium supplemented with 2.5% fetal bovine serum at 37°C for 30 min with 0.2 mg/ml 3-chloro-4-diaminobenzidine. Histological features of mucosal inflammation, epithelial damage, and lymphoid follicle formation were graded on a scale of 0–3 for each specimen under a light microscope (magnification, $\times 25$), and the median score was used. According to the Sydney system (27), neutrophil infiltration into the mucosa was evaluated as follows: 0, none; 1, mild; 2, moderate; and 3, severe. As described by Atherton et al. (1), epithelial damage was graded as follows: 0, no exfoliation; 1, exfoliation of <30% of epithelium; 2, 30–70% exfoliation; and 3, >70% exfoliation. Similarly, lymphoid follicle formation was also graded as follows: 0, no follicle; 1, follicles of <30% under the muscularis mucosa; 2, 30–70% follicles; and 3, >70% follicles.

**Determination of viable H. pylori.** Viable H. pylori in the stomach was assayed according to our previously reported method (34). The animals were killed, and their stomachs were excised. The tissues were homogenized in 20 ml PBS. The diluted homogenates were applied onto Brucella agar (GIBCO BRL) plates supplemented with 10% horse blood (Nippon Bio-Test, Tokyo, Japan) and (in $\mu$g/ml) 2.5 amphotericin B (Sigma, St. Louis, MO), 9 vancomycin (Sigma), 0.32 polymyxin B (Sigma), 5 trimethoprim (Sigma), and 50 2,3,5-triphenyltetrazolium chloride (Wako Pure Chemicals). The plates were incubated at 37°C under a microaerophilic atmosphere for 7 days. The number of colonies was counted, and viable H. pylori was expressed as CFU per stomach.

**Determination of neutrophil chemokine, interferon-$\gamma$, and interleukin-10 production.** The production of cytokine-induced neutrophil chemotactant [CINC/KC, interleukin (IL)-8 family chemokine in rodents], interferon (IFN)-$\gamma$, and IL-10 were assayed according to the method of Noach et al. (26) with slight modifications. Gastric specimens (the fundus near the antrum) were taken from normal and H. pylori-infected animals. After being washed with PBS, the tissues were minced and then incubated in 1 ml of Dulbecco’s modified Eagle’s medium supplemented with 2.5% fetal bovine serum and the above antibiotics at 37°C for 20 h under 5% CO$_2$ in air. Thereafter, the tissues were homogenized in the culture medium containing 0.1 mM phenylmethylsulfonyl fluoride and 1 $\mu$g/ml leupeptin. The homogenates were centrifuged at 10,000 g for 20 min. The amounts of CINC/KC, IFN-$\gamma$, and IL-10 in the resulting supernatants were determined by enzyme immunoassay (CINC/KC EIA kit; Immuno Biological Laboratories, Fujioka, Japan) and ELISA (IFN-$\gamma$ ELISA kit and IL-10 ELISA kit; Biosource International, Camarillo, CA), respectively. CINC/KC, IFN-$\gamma$, and IL-10 production was expressed as picograms per milligram tissue per 20 h.

**Drugs.** NS-398 (kindly synthesized by Nippon Chemipharm, Tokyo, Japan) and indomethacin (Sigma) were finely dispersed in Tween 80 (10 mg/50 ml) and then suspended by adding saline to the desired concentrations. In our preliminary experiment, NS-398 at 20 mg/kg, but not at 10 mg/kg, had inhibited PGE$_2$ production in normal mucosa, indicating that 10 mg/kg NS-398 was ineffective in COX-1 activity. In addition, indomethacin even at 2 mg/kg had potently reduced PGE$_2$ levels in normal mucosa, but repeated administration of 5 mg/kg indomethacin had been lethal to H. pylori-infected gerbils. Therefore, the doses of 10 mg/kg and 2 mg/kg were...
selected for NS-398 and indomethacin, respectively. The
drugs were subcutaneously administered once daily for 4 wk
from 2 wk of H. pylori infection. The animals were given the
drugs in a volume of 10 ml/kg body wt. Control animals
received the vehicle alone.

Statistical analysis. Data are presented as means ± SE of
3–6 animals/group. Statistical differences were evaluated by
Student’s t-test or Mann-Whitney U-test. P values of < 0.05
were considered significant.

RESULTS

COX-2 induction in the gastric mucosa by H. pylori
infection. In our model of H. pylori infection, H. pylori
is colonized for at least 10 mo in the gastric mucosa of
all gerbils given the bacteria (20, 34). The number of
viable H. pylori in the stomach reached a plateau level
from 2 wk after the inoculation. In addition, gastritis
with hemorrhagic mucosal lesions and gastric ulcers
were generated only in the fundus near the antrum
from 4 wk and 20 wk of the infection, respectively (20,
34). Thus the region is highly sensitive to H. pylori,
and the following parameters, except for H. pylori viability,
were measured in the region.

At first, we examined the expression of COX proteins
and PGE2 production in the gastric mucosa during H.
pylori infection (Fig. 1). On Western blot analysis,
COX-1 protein was detected both in normal mucosa
and in the mucosa with H. pylori infection. The level of
COX-1 protein remained nearly constant during the
infection. In contrast, COX-2 protein was not found in
normal or H. pylori-infected (2 wk) mucosa, but H.
pylori infection for 4 wk induced the expression of
COX-2 protein. PGE2 production in normal mucosa
was 36.7 ± 5.6 pg·mg⁻¹·h⁻¹. At 2 wk of H. pylori
infection, there was no difference in PGE2 production
compared with the normal level. However, PGE2 pro-
duction was significantly elevated from 4 wk of the
infection compared with that in normal mucosa. There
was a correlation between the increase in PGE2 pro-
duction and the intensity of the COX-2 protein band.

Effects of NS-398 and indomethacin on H. pylori-
induced PGE2 production and gastritis. As shown in
Fig. 1, the increase in PGE2 production was associated
with COX-2 induction in the H. pylori-infected mucosa.
To investigate the role of COX-2 in H. pylori-induced
gastritis, we examined the effects of NSAIDs on PGE2 pro-
duction and gastric pathology caused by H. pylori.

NS-398 (a COX-2-selective inhibitor) at 10 mg/kg or
indomethacin (a nonselective COX inhibitor) at 2
mg/kg was administered for 4 wk to normal and H. pylori-infected animals. NS-398 failed to inhibit
PGE2 production in normal mucosa but significantly
reduced the H. pylori-increased PGE2 production (Fig. 2).
In contrast, indomethacin potently inhibited PGE2
production in both normal and H. pylori-infected mu-
cosa. Significant differences were observed between
the effects of NS-398 and indomethacin in the H. pylo-
ri-infected animals.

In the control animals with H. pylori infection, there
were hemorrhagic mucosal lesions of 1.0 ± 0.4 mm².
Erosive lesions were apparently enlarged by treatment.
with NS-398 and indomethacin, although there were no significant differences between the drug-treated and control groups. Erosive area was 1.7 ± 0.6 mm² and 2.0 ± 0.6 mm² in NS-398- and indomethacin-treated groups, respectively.

Neutrophil infiltration, epithelium damage, and lymphoid follicle formation were also evaluated as shown in Figs. 3 and 4. H. pylori infection caused marked infiltration of neutrophils into the gastric mucosa and epithelium damage. Furthermore, lymphoid follicles were generated in the submucosa. Both NS-398 and indomethacin significantly aggravated the H. pylori-induced neutrophil infiltration, epithelium damage, and lymphoid follicle formation. The aggravation of neutrophil infiltration appeared to be more severe in indomethacin-treated animals than in NS-398-treated ones. Epithelium damage was also more significant and lymphoid follicles more enlarged by indomethacin than by NS-398. However, repeated administration of NS-398 for 4 wk induced no inflammation or damage in normal animals. Similarly, indomethacin did not cause appreciable pathological changes in normal animals.

Effects of NS-398 and indomethacin on H. pylori infection and the production of CINC/KC, IFN-γ, and IL-10. Since NS-398 and indomethacin aggravated H. pylori-induced gastritis, we determined the number of viable H. pylori in the stomach after treatment with the drugs. The number of H. pylori colonized in the stomach was 2.19 ± 0.56 × 10⁵ CFU in the control group. Both NS-398 (1.92 ± 0.42 × 10⁵ CFU) and indomethacin (1.51 ± 0.38 × 10⁵ CFU) tended to reduce H. pylori number, but there were no significant differences between the drug-treated and control groups.

We next examined the effects of NS-398 and indomethacin on the production of CINC/KC (a predominant neutrophil chemokine in rodents) and IFN-γ in the gastric mucosa (Fig. 5). H. pylori infection for 6 wk significantly increased CINC/KC and IFN-γ production by ~23- and ~8-fold, respectively, compared with the production in normal mucosa. Both NS-398 and indomethacin significantly potentiated the H. pylori-increased CINC/KC and IFN-γ production. Treatment with NS-398 and indomethacin further promoted CINC/KC production by 2.0- and 2.8-fold, respectively, compared with the H. pylori-infected control group. The IFN-γ production in the NS-398- and indomethacin-treated groups was also increased by 1.6- and 2.0-fold, respectively, compared with the control with H. pylori infection.

IL-10 was not detected in normal mucosa, whereas its production was slightly induced by H. pylori infection (0.28 ± 0.09 pg·mg⁻¹·20 h⁻¹). However, the IL-10 production in the H. pylori-infected mucosa was not affected by either NS-398 or indomethacin.

Neither NS-398 nor indomethacin increased the cytokine production in normal animals. Similar to the effects on gastric pathology, indomethacin had a stronger effect on H. pylori-induced CINC/KC and IFN-γ production than NS-398.

![Fig. 3. Histological appearance of pathological changes in the gastric mucosa of H. pylori-infected gerbils. Vehicle (control), 10 mg/kg NS-398, or 2 mg/kg indomethacin was administered for 4 wk to normal and H. pylori-infected gerbils. A: normal mucosa. B: H. pylori-infected mucosa in control animals. C: H. pylori-infected mucosa in NS-398-treated animals. D: H. pylori-infected mucosa in indomethacin-treated animals. H. pylori-induced neutrophil infiltration, lymphoid follicles, and epithelium damage were aggravated by NS-398 and indomethacin. Magnification, ×25.](http://ajpgi.physiology.org/)
In the present study, *H. pylori* infection for >4 wk induced COX-2 expression in the gastric mucosa of Mongolian gerbils. Recent studies with human gastric specimens also revealed that COX-2 expression is absent in normal mucosa but is profoundly induced in *H. pylori*-positive gastritis (22, 31, 33). In contrast, COX-1 protein was constitutively expressed in both normal and *H. pylori*-infected mucosa of gerbils. PGE$_2$ produc-
In response to *H. pylori* infection, mucosal defense mechanisms might be activated. Because PGs are important defensive factors in the gastric mucosa (9, 28), COX-2 induction is reasonable for protection of the mucosa against *H. pylori*. PGE2 increases blood flow and secretion of mucus and bicarbonate, inhibits acid secretion, and directly protects gastric cells against toxic stimuli (9). We reported that *H. pylori* infection for 2 and 4 wk causes an increase in mucus synthesis in the gastric mucosa of gerbils and that both NS-398 and indomethacin suppress the increased mucus synthesis (35). The decreases in these PG defensive responses to *H. pylori* infection are suggested to contribute to aggravation of mucosal inflammation caused by COX inhibition.

In addition, downregulation of proinflammatory cytokine expression by PGs is also likely to be important for mucosal protection against *H. pylori* infection. In the patients with *H. pylori*-positive gastritis, the IL-8 level in the gastric mucosa is significantly higher than in ones with *H. pylori*-negative gastritis (6, 42). Similarly, in our gerbil model, CINC/KC production was induced by *H. pylori* infection. NS-398 and indomethacin significantly potentiated CINC/KC production in *H. pylori*-infected mucosa. CINC/KC belongs to the IL-8 chemokine family and is considered to play a crucial role in neutrophil infiltration in rodents because rodent counterparts of IL-8 have not been identified (40). The increased CINC/KC production accounts for enhancement of neutrophil infiltration by the NSAIDs in *H. pylori*-infected mucosa. These results suggest that PGs, derived from COX-2 as well as COX-1, downregulate CINC/KC production, resulting in suppression of neutrophil infiltration in *H. pylori*-infected mucosa.

Gastric mucosal T-lymphocyte response to *H. pylori* infection is dependent predominantly on type 1 helper T-lymphocytes, which are characterized as IFN-γ-secreting cells (8, 10, 19). Mohammadi et al. (25) reported that in vivo neutralization of IFN-γ by administration of anti-IFN-γ antibody causes a significant reduction of gastric inflammation induced by *Helicobacter felis* in mice. Irisawa et al. (17) reported that *H. pylori*-induced mucosal damage is augmented by the overexpression of IFN-γ in the stomach of mice. Furthermore, Sawai et al. (30) reported that there is no inflammatory pathology in the gastric mucosa of *H. pylori*-infected IFN-γ gene-deficient mice, whereas inflammatory cell infiltration and erosions are observed in the mucosa of *H. pylori*-infected wild-type mice. Consequently, it has been widely accepted that IFN-γ is one of the important causal factors for *H. pylori*-associated diseases. We also confirmed that *H. pylori* infection increases IFN-γ production in gerbils and found that the increase in IFN-γ production is potentiated by NS-398 and indomethacin. Similar to the case of CINC/KC production, these results suggest that PGs, derived from both COX-1 and COX-2, downregulate IFN-γ production, resulting in an attenuation of mucosal inflammation induced by *H. pylori* infection.

In contrast, IL-10 production was induced by *H. pylori* infection, as observed in human patients (42), but was not affected by NS-398 or indomethacin. IL-10 has been shown to inhibit the production of cytokines, including IL-8 and IFN-γ (2, 7). The failure to promote IL-10 level did not attenuate the NSAID-increased production of CINC/KC and IFN-γ in *H. pylori*-infected mucosa. In addition, the fact that NSAIDs had no effect on IL-10 production suggests that the NSAID-induced increases in CINC/KC and IFN-γ levels are due to the increased production and do not result from the inhibition of peptidase activity during culturing.

The number of viable *H. pylori* in the stomach was reduced by NS-398 and indomethacin, although there...
were no significant differences between the drug-treated and control groups. This result indicates that the deleterious effects of the NSAIDs on the gastric mucosa do not result from the increase in the number of viable \( H. pylori \). Caselli et al. (4) reported the similar result that, in \( H. pylori \)-positive patients with rheumatoid arthritis, the \( H. pylori \)-positive rate is significantly reduced by NSAID treatment compared with the non-treated group. To our knowledge, there have been no reports that NSAIDs possess an anti-\(H. pylori\) activity, and we confirmed that the minimal inhibitory concentration of indomethacin toward \( H. pylori \) is 50 \( \mu \)g/ml and is quite a bit higher than that of clarithromycin (0.06 \( \mu \)g/ml). An attenuation of mucus synthesis may be related to the decrease in \( H. pylori \) number. The gastric mucus layer is known to serve as the major habitat of \( H. pylori \), and NSAIDs inhibit the increased mucus synthesis in \( H. pylori \)-infected mucosa of gerbils. Alternatively, the increase in IFN-\( \gamma \) production may result in the decrease in \( H. pylori \) number. In a recent study by Sawai et al. (30), the number of \( H. pylori \) in the stomach in IFN-\( \gamma \) gene-deficient mice was higher than that in wild-type mice, suggesting that IFN-\( \gamma \) plays a protective role in \( H. pylori \) infection. Interestingly, we found that IFN-\( \gamma \), in concert with \( H. pylori \), potently reduces mucus secretion by cultured gastric epithelial cells (36).

COX-2-selective inhibitors are expected as new NSAIDs without ulcerogenic effect. In fact, COX-2-selective NSAIDs such as nimesulide and celecoxib are clinically used as anti-inflammatory drugs, but the incidences of their gastric side effects are significantly lower than those of conventional NSAIDs. However, our results suggest the possibility that COX-2-selective NSAIDs may have an injurious effect on the gastric mucosa of \( H. pylori \)-positive patients. Wallace et al. (39) reported that, to achieve a desirable anti-inflammatory effect, COX-2-selective NSAIDs needed to be given at high doses in which both COX-1 and COX-2 activities are inhibited. If so, the safety of COX-2-selective NSAIDs may be lowered, especially in \( H. pylori \)-infected patients. Overall, independent of type of NSAID, NSAID users should be aware of these side effects if they are infected with \( H. pylori \). In the case of application of COX-2-selective NSAIDs to preexisting gastric ulcers, the drugs also exert an unfavorable effect. We previously reported that gastric ulcer healing is significantly impaired by NS-398 at low doses in which COX-2 activity only is inhibited in rats (32).

We conclude that COX-2 as well as COX-1 has an anti-inflammatory effect in \( H. pylori \)-induced gastritis in Mongolian gerbils. COX-2-selective inhibitors may aggravate gastritis if used in \( H. pylori \)-positive patients.

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 ROLE OF COX-2 IN H. PYLORI-INDUCED GASTRITIS


