Pathogenic Importance of Cysteinyl Leukotrienes in Development of Gastric Lesions Induced by Ischemia/Reperfusion in Mice

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ABSTRACT

We examined the role of cysteinyl leukotrienes (CysLTs) in the gastric ulcerogenic response to ischemia/reperfusion (I/R) in mice. Experiments were performed in male C57BL/6J mice after 18-h fasting. Under urethane anesthesia, the celiac artery was clamped for 30 min, and then reperfusion was achieved by removing the clamp. The stomach was examined for lesions 60 min thereafter. The severity of I/R-induced gastric damage was reduced by prior administration of pranlukast [CysLT receptor type 1 (CysLT1R) antagonist], as well as 1-[5′-(3′-methoxy-4′-ethoxycarbonyl-oxophenyl)-2′,4′-pentadienoyl]aminoethyl]-4-diphenylmethoxypiperidine [TMK688; 5-lipoxygenase (5-LOX) inhibitor]. On the contrary, these lesions were markedly worsened by pretreatment with indomethacin, and this response was abrogated by the coadministration of TMK688 or pranlukast. The gene expression of CysLT1R, but not 5-LOX was up-regulated in the stomach after I/R, but both expressions were increased under I/R in the presence of indomethacin. I/R slightly increased the mucosal CysLT content of the stomach, yet this increase was markedly enhanced when the animals were pretreated with indomethacin. The increased CysLT bio-synthetic response to indomethacin during I/R was attenuated by TMK688. Indomethacin alone caused a slight increase of CysLT,R expression and markedly up-regulated 5-LOX expression in the stomach. We concluded that I/R up-regulated the expression of CysLT,R in the stomach; CysLTs play a role in the pathogenesis of I/R-induced gastric damage through the activation of CysLT,R; and the aggravation by indomethacin of these lesions may be brought about by the increase of CysLT production and the up-regulation of 5-LOX expression, in addition to the decreased prostaglandin production.
products, LTC₄, LTD₄, and LTE₄, referred to as cysteinyl LTs (CysLTs), are recognized as potent inflammatory mediators (Murakami et al., 1995; Gronert et al., 2001). CysLTs are generated from cell membrane phospholipid-associated arachidonic acids by 5-LOX and are reported to play a pathogenic role in the development of I/R-induced damage in kidney, liver, and bladder (Takamatsu et al., 2004; Sener et al., 2006, 2007). However, it remains unknown whether CysLTs are involved in the development of gastric lesions under I/R.

Recently, two subtypes of CysLT receptors, CysLT₁R and CysLT₂R, have been characterized, both of which are classic G protein-coupled receptors with seven transmembrane domains (Brink et al., 2003). It has been reported that CysLT₁R is highly expressed in spleen, small intestine, colon, heart, pancreas, kidney, liver, and placenta (Lynch et al., 1999; Sarau et al., 1999) and detected in mast cells, mononuclear cells, and microvascular endothelia by in situ hybridization or immunohistochemistry (Lynch et al., 1999; Zhang et al., 2004). Several studies showed that the administration of a 5-LOX inhibitor or a selective CysLT₂R antagonist reduced the severity of ethanol- or nonsteroidal anti-inflammatory drug-induced gastric injury by inhibiting neutrophil adhesion (Sala and Folco, 2001; Dengiz et al., 2007), suggesting the pathogenic importance of CysLTs/CysLT₁R in gastric lesions. Because CysLT₁R, found in pulmonary vein preparations by pharmacological assays, has now been reported to express in various tissues (Brink et al., 2003; Kanoaka and Boyce, 2004; Moos et al., 2008), it is possible that CysLT₁R may also play a role in the pathogenesis of gastric lesions as induced by I/R. However, none of the selective CysLT₂R antagonists is available for in vivo studies.

In the present study, we thus focused on CysLTs and CysLT₁R and examined the effects of a 5-LOX inhibitor and a selective CysLT₂R antagonist on I/R-induced gastric damage in mice and investigated the roles of CysLTs/CysLT₁R in mucosal defense during I/R. In addition, we examined the mechanism by which indomethacin aggravates I/R-induced lesions, in relation to CysLTs/CysLT₁R as well as 5-LOX in the stomach.

Materials and Methods

Animals. Male C57BL/6J mice (3 months old; SLC, Shizuoka, Japan) were used. The animals were deprived of food but allowed free access to tap water for 18 h before the experiments. All experiments were carried out using five to eight mice under urethane anesthesia, unless otherwise specified. The experimental procedures were approved by the Experimental Animal Research Committee of Kyoto Pharmaceutical University.

Induction of Ischemia and Reperfusion-Induced Gastric Damage. Acute gastric mucosal lesions were produced by I/R in mice, according to a modified method reported by Wada et al. (1996). In brief, under urethane anesthesia (1.25 g/kg i.p.), the celiac artery was clamped with a small clamp (disposable vascular clip; holding force 40 g; BEAR Medical Corporation, Chiba, Japan), and 30 min later reperfusion was achieved through removal of the clamp. In a preliminary study, we found that macroscopically visible lesions were consistently observed in the stomach 60 min after the onset of reperfusion following ischemia for 30 min. The effect of various treatments on the formation of lesions was assessed 60 min after the reperfusion, according to a previous study (Yoshikawa et al., 1989). After reperfusion for 60 min, the stomach was excised, inflated by injecting 0.4 ml of 2% formalin for 10 min to fix the tissue walls, and opened along the greater curvature. Pranlukast (a CysLT₁R antagonist; 0.1–10 mg/kg; Nishio et al., 2007), montelukast (a CysLT₁R antagonist; 3 mg/kg), or TMK688 (a 5-LOX inhibitor; 3–30 mg/kg; Konaka et al., 1999) was administered orally 60 min before ischemia. Indomethacin (a nonselective COX inhibitor; 5 mg/kg) was given subcutaneously 30 min before ischemia. The area (square millimeters) of hemorrhagic lesions developed in the stomach was measured under a dissecting microscope (Olympus, Tokyo, Japan) with a square grid (×10). The person measuring the lesions did not know the treatments given to the animals. In some cases, the gastric mucosa was examined with a light microscope, and the animals were killed after I/R treatment, and the stomachs were excised. The tissue samples were then immersed in 2% formalin-saline, embedded in paraffin, sectioned at 4 µm, and stained with hematoxylin and eosin.

Determination of Myeloperoxidase Activity. Myeloperoxidase (MPO) activity in the gastric mucosa was measured after I/R treatment in mice, according to a modified version of the method of Krawisz et al. (1984). At 60 min after I/R treatment, the animals were sacrificed by the withdrawal of blood from the heart through perfusion with saline, and the stomach was excised. After rinsing the tissue with cold saline, the mucosa was scraped with glass slides, weighed, and homogenized in a 50 mM phosphate buffer containing 0.5% hexadecyl-trimethyl-ammonium bromide, pH 6.0 (Sigma-Aldrich, St. Louis, MO). The homogenized samples were subjected to freezing and thawing three times, and centrifuged at 2000 g for 10 min at 4°C. MPO activity in the supernatant was determined by adding 50 µl of the supernatant to 50 µl of 10 mM phosphate buffer, pH 6.0, and 50 µl of 1.5 M o-dianisidine dihydrochloride (Sigma-Aldrich) containing 0.0005% (w/v) hydrogen peroxide. The changes in absorbance at 450 nm were recorded on a microplate reader (VERSAmax; Molecular Devices, Sunnyvale, CA). Sample protein content was estimated by spectrophotometric assay (protein assay kit; Pierce Chemical, Rockford, IL), and the MPO activity was obtained from the slope of the reaction curve, based on the following equation: specific activity (micromoles of H₂O₂ per minute per milligram of protein) = (OD/min)/(OD/µmol H₂O₂ × mg protein), where OD is optical density. Pranlukast (3 mg/kg) or TMK688 (30 mg/kg) was administered orally 60 min before ischemia, whereas indomethacin was given subcutaneously 30 min before ischemia.

Measurement of Mucosal CysLT Levels. Levels of CysLT in the gastric mucosa were measured after I/R treatment in mice. TMK688 (30 mg/kg) or pranlukast (3 mg/kg) was administrated orally alone or 60 min before ischemia, whereas indomethacin was given subcutaneously 30 min before ischemia. The animals were killed under deep ether anesthesia after the 60-min reperfusion period, and the gastric mucosa was isolated, weighed, and placed in a tube containing 100% methanol. Then, the tissues were homogenized by a Polytron homogenizer (IKA, Tokyo, Japan) and centrifuged at 12,000g for 10 min at 4°C. After the supernatant of each sample had been evaporated with N₂ gas, the residue was resolved in assay buffer and used for the determination of CysLTs. Concentrations of CysLTs were measured using a CysLT enzyme immunoassay kit (Cayman Chemical, Ann Arbor, MI).

Analyses of Expression of 5-LOX and CysLT₁R mRNAs by RT-PCR. Animals were killed under deep ether anesthesia 60 min after I/R treatment in the absence or presence of indomethacin (5 mg/kg) given subcutaneously 30 min before the ischemia, and the stomachs were removed, frozen in liquid nitrogen, and stored at −80°C before use. In some cases, the animals were given TMK688 (30 mg/kg) or indomethacin (5 mg/kg) alone without I/R treatment and killed 60 min later. Tissue samples were pooled from two to three mice for extraction of total RNA, which was prepared by a single-step acid phenol-chloroform extraction procedure by use of Sepasol RNA-I (Nacalai Tesque, Kyoto, Japan). Total RNA primed by random hexadeoxy ribonucleotide was reverse-transcribed with the SuperScript premplification system (Invitrogen, Carlsbad, CA). The sequences of sense and antisense primers for mouse glyceraldehyde-3-phosphate dehydrogenase (GAPDH), 5-LOX, and CysLT₁R are...
listed in Table 1. An aliquot of the reverse transcription reaction product served as a template in 35 cycles of PCR with 1 min of denaturation at 95°C and 1 min of annealing at 68°C by Advantage-2 PCR kit (BD Biosciences, Palo Alto, CA) on a thermal cycler. A portion of the PCR mixture was electrophoresed in a 1.5% agarose gel in Tris-EDTA-acetic acid buffer, and the gel was stained with ethidium bromide and photographed. Images were analyzed with the ImageJ version 1.39 (National Institutes of Health, Bethesda, MD), and the semiquantitative measurement of mRNA expression was presented as a ratio compared with GAPDH.

**Determination of Gastric Acid Secretion.** Acid secretion was measured in pylorus-ligated mice. Animals were deprived of food for 18 h and water for 2 h before the operation. Under light ether anesthesia, the abdomen was opened and the pylorus was ligated. Then, the animals were then allowed to recover from the anesthesia. TMK688 or pranlukast was given intraduodenally immediately after pylorus ligation. Two hours after pylorus ligation, the animals were sacrificed with an overdose of ether, and the gastric contents were measured in pylorus-ligated mice. Animals were deprived of food for 18 h and water for 2 h before the operation. Under light ether anesthesia, the animals were administered orally, intraduodenally, or subcutaneously in a volume of 0.1 ml/20 g body weight. Control animals received hydroxypropylcellulose as the vehicle.

**Statistical Analysis.** Data are presented as the mean ± S.E. for five to eight rats per group. Statistical analyses were performed using one-way analysis of variance and Student’s t test or Dunnnett’s multiple comparison test where appropriate. Values of P < 0.05 are considered significant.

**Results**

**Effects of TMK688 and Pranlukast on I/R-Induced Gastric Damage in Mice.** Laparotomy without clamping of the gastric artery (sham operation) did not produce any damage in the gastric mucosa. In the animals subjected to I/R treatment (30 min of ischemia followed by reperfusion for 60 min), however, multiple hemorrhagic lesions were observed in the gastric mucosa, with the lesion score being 11.2 ± 1.4 mm² (Fig. 1A). Ischemia for 30 min did not induce any macroscopically visible damage in the mucosa (data not shown). Pretreatment of the animals with TMK688 (3–30 mg/kg p.o.), a 5-LOX inhibitor, dose-dependently prevented the I/R-induced development of gastric lesions, with the inhibition at 30 mg/kg being 49.1%, which is significant compared with the control.

To further investigate the involvement of CysLTs in the pathogenesis of I/R-induced gastric lesions, we examined the effect of pranlukast, a CysLT₁R antagonist, on the gastric ulcerogenic response to I/R. As shown in Fig. 1B, the severity of the gastric lesions was reduced by the prior administration of pranlukast (0.1–10 mg/kg p.o.), in a dose-dependent manner, and a significant effect was observed at 1 mg/kg or greater, with the inhibition at 1, 3, and 10 mg/kg being 44.4, 72.2, and 74.0%, respectively. A significant protection was similarly obtained by montelukast (5 mg/kg), another CysLT₁R antagonist, the inhibition being 73.6% (3.9 ± 0.7 versus 14.8 ± 1.8 mm²).

In a sham-operated animal without I/R treatment, no damage was detected even by histological observation (Fig. 2A). By contrast, severe damage was observed histologically in the stomach after I/R treatment; most of the damage was restricted to the surface epithelium, but some damage occurred deep in the mucosa, extending to the region of pits and glands (Fig. 2B). When the animal was pretreated with TMK688 (30 mg/kg p.o.) or pranlukast (3 mg/kg p.o.), the severity of the histological damage was markedly reduced.
and only slight damage was observed in the surface epithelium (Fig. 2, C and D).

Effects of TMK688 and Pranlukast on I/R-Induced Gastric Damage in Mice Pretreated with Indomethacin. It has been shown that COX inhibition stimulates the production of LTs by inducing a shift in balance from protective PGs to proulcerogenic CysLTs (Peskar, 1991) and that I/R-induced gastric injury was markedly aggravated by prior administration of indomethacin, a nonselective COX inhibitor (Kotani et al., 2006). We therefore examined the effects of 5-LOX inhibitor and CysLT1R antagonist on I/R-induced gastric ulceration in the mice pretreated with indomethacin.

When the stomach was subjected to I/R in the presence of indomethacin (5 mg/kg s.c.), the severity of gastric lesions was significantly increased, with the lesion score being 10.3 ± 2.3 mm², approximately 2.5 times greater than that (8.3 ± 1.5 mm²) for I/R alone (Fig. 3). This effect of indomethacin was significantly abrogated by cotreatment with either TMK688 (30 mg/kg p.o.) or pranlukast (3 mg/kg p.o.), with the inhibition being 40.4 and 70.0%, respectively.

Effects of TMK688 and Pranlukast on MPO Activity in Mouse Stomachs after I/R. It is known that I/R-induced gastric injury is accompanied by an increase in neutrophil recruitment in the mucosa (Kotani et al., 2006, 2007). In the present study, the severity of the I/R-induced gastric lesions was decreased by prior administration of indomethacin, a nonselective COX inhibitor (Kotani et al., 2006). We therefore examined the effects of 5-LOX inhibitor and CysLT1R antagonist on I/R-induced gastric ulceration in the mice pretreated with indomethacin.

When the stomach was subjected to I/R in the presence of indomethacin (5 mg/kg s.c.), the severity of gastric lesions was significantly increased, with the lesion score being 20.3 ± 2.3 mm², approximately 2.5 times greater than that (8.3 ± 1.5 mm²) for I/R alone (Fig. 3). This effect of indomethacin was significantly abrogated by cotreatment with either TMK688 (30 mg/kg p.o.) or pranlukast (3 mg/kg p.o.), with the inhibition being 40.4 and 70.0%, respectively.

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Fig. 3. Effects of TMK688 and pranlukast on I/R-induced gastric lesions in mice pretreated with indomethacin. Under urethane anesthesia, the celiac artery was clamped (ischemia), and reperfusion was achieved 30 min later by removal of the clamp. After a 60-min reperfusion period, gastric lesions were evaluated. Indomethacin (5 mg/kg) was given subcutaneously 30 min before ischemia, whereas TMK688 (30 mg/kg) or pranlukast (3 mg/kg) was given orally 60 min before. Data are presented as the mean ± S.E. for five to seven mice. Significant difference at *, P < 0.05 from control and #, from vehicle.

Fig. 4. Effects of TMK688 and pranlukast on changes in gastric mucosal MPO activity induced by I/R in mice. Under urethane anesthesia, the celiac artery was clamped (ischemia), and then reperfusion was achieved 30 min later by removal of the clamp. After a 60-min reperfusion period, gastric MPO activity was measured. TMK688 (30 mg/kg) or pranlukast (3 mg/kg) was given orally 60 min before ischemia. Data are presented as the mean ± S.E. for five to six mice. Significant difference at *, P < 0.05 from sham and #, from control (I/R alone).
activity in control mice was $0.044 \pm 0.006 \mu mol H_2O_2/min/mg$ protein when determined 60 min after I/R treatment (Fig. 5). The I/R-induced increase of MPO activity was markedly enhanced in the animals pretreated with indomethacin ($5 \text{ mg/kg s.c.}$), with the values being $0.11 \pm 0.013 \mu mol H_2O_2/min/mg$ protein. This response was significantly suppressed by the prior administration of TMK688 ($30 \text{ mg/kg p.o.}$) or pranlukast ($3 \text{ mg/kg p.o.}$), with the inhibition being 56.4 and 58.2%, respectively.

Changes in Mucosal CysLT Content of Mouse Stomach after I/R with or without Indomethacin. To further investigate the role of CysLTs in the I/R-induced development of gastric lesions, we measured the mucosal CysLT levels in the mouse stomach in the absence or presence of indomethacin.

The levels of CysLTs in the gastric mucosa were not changed after I/R treatment compared with the sham operation, with the values being $3.3 \pm 0.2 \text{ ng/mg tissue}$ in the sham-operated group and $2.4 \pm 0.3 \text{ ng/mg tissue}$ in the I/R-treated group. Pretreatment with TMK688 ($30 \text{ mg/kg p.o.}$) inhibited the production of CysLTs in the gastric mucosa subjected to I/R treatment and significantly decreased the levels to approximately half of control values (Fig. 6). Pretreatment of the animals with indomethacin ($5 \text{ mg/kg s.c.}$), however, significantly increased the mucosal levels of CysLTs to $7.0 \pm 1.3 \text{ ng/mg tissue}$ under I/R, and this response was almost totally suppressed by cotreatment with TMK688 ($30 \text{ mg/kg}$), with the inhibition being $90.6\%$. Pranlukast ($3 \text{ mg/kg p.o.}$) had no effect on the mucosal CysLT levels in the stomach after I/R treatment, in the absence or presence of indomethacin.

Expression of CysLT$_R$ and 5-LOX mRNAs in Mouse Stomach after I/R. GAPDH mRNA, the housekeeping gene, was clearly detectable in the stomach of control mice, and its expression remained unaffected following I/R. Although CysLT$_R$ was expressed in the gastric mucosa subjected to the sham operation, the expression was markedly up-regulated after I/R treatment when examined 1 h after reperfusion (Fig. 7). Ischemia alone had no effect on the CysLT$_R$ expression (data not shown). Indomethacin ($5 \text{ mg/kg}$ s.c.) alone slightly up-regulated the expression of CysLT$_R$ in the gastric mucosa but did not further enhance the increased expression after I/R. 5-LOX mRNA was also observed in the normal stomach after the sham operation and remained unchanged after I/R treatment when examined 1 h after reperfusion. Ischemia alone did not affect the 5-LOX expression in the gastric mucosa (data not shown). However, the mucosal expression of 5-LOX under I/R was significantly increased by pretreatment of the animals with indomethacin ($5 \text{ mg/kg}$) compared with the control mouse stomach subjected to I/R alone (Fig. 8). It was also found that indomethacin by itself caused a marked up-regulation of 5-LOX expression in the stomach, and the increased expression by indomethacin was not further enhanced by additional I/R treatment. TMK688 ($30 \text{ mg/kg p.o.}$) did not affect the expression of 5-LOX as well as CysLT$_R$ in the gastric mucosa with or without I/R treatment (data not shown).

Effects of TMK688 and Pranlukast on Gastric Acid Secretion. The acid output in normal mouse stomachs was $1.00 \pm 0.12 \text{ Eq/h}$ when determined by a 2-h pylorus ligation (Table 2). Neither TMK688 ($30 \text{ mg/kg i.d.}$) nor pranlukast ($3 \text{ mg/kg i.d.}$) had any effect on the basal acid output in mice.

Discussion

The supply of blood to ischemic tissues paradoxically exacerbates the injury process and leads to the production of free radicals and proinflammatory mediators, and the attraction of inflammatory cells infiltrating the tissues (Farber et al., 1981; Piper et al., 2003). Although there is a substantial body...
of experimental data characterizing the factors that reduce or enhance the severity of I/R-induced gastric lesions, the roles of CysLTs in the pathogenesis remain unknown. The present study demonstrated that I/R markedly up-regulated CysLT1R expression in the gastric mucosa with a slight increase of CysLT production and that both a 5-LOX inhibitor and a CysLT1R antagonist suppressed the development of gastric lesions in response to I/R, strongly suggesting the involvement of CysLTs as a pathogenic factor in I/R-induced gastric damage. In addition, we observed a marked aggravation of these lesions on pretreatment with indomethacin, consistent with our previous observations (Takeuchi et al., 1986; Kotani et al., 2006), and we further showed the underlying mechanism of this response to be associated with the up-regulation of 5-LOX expression and CysLT production in the stomach.

The arachidonic acids released by phospholipase A2 serve as substrates for the production of a group lipid mediators known as LTs, which induce proinflammatory signaling through the activation of CysLTs and LTB4 receptors. 5-LOX is the key enzyme in the biosynthesis of LTs from arachidonic acids. LTs, potent mediators of inflammatory and allergic reactions, are locally released from leukocytes and other 5-LOX-expressing cells, and they exert their effects by binding to specific membrane receptors (Maekawa et al., 2002). CysLT receptors exist in two subtypes, CysLT1R and CysLT2R, and they are expressed in various tissues and inflammatory cells (Lynch et al., 1999; Sarau et al., 1999; Brink et al., 2003). Sala and Folco (2001) reported that a selective CysLT1R antagonist reduced the severity of ethanol- or nonsteroidal anti-inflammatory drug-induced gastric lesions by inhibiting neutrophil adhesion, suggesting the pathogenic importance for CysLT1R. Certainly, CysLT2R may also play a role in the pathogenesis of gastric lesions. However, none of the selective CysLT2R antagonists is available for in vivo studies. In the present study, we thus focused on CysLTs/CysLT1R and investigated the effects of a 5-LOX inhibitor and a selective CysLT1R antagonist on I/R-induced gastric damage.

First, we found that both pranlukast, a CysLT1R antagonist, and TMK688, a 5-LOX inhibitor, significantly reduced the severity of I/R-induced gastric lesions. CysLTs are reportedly known to increase vascular permeability, neutrophil invasion, and inflammatory cytokine production (Sala and Folco, 2001; Maekawa et al., 2002; Profita et al., 2008). Because I/R-induced damage is a neutrophil-dependent response (Zimmerman and Granger, 1990), it is assumed that the protective effect of pranlukast is brought about, at least

<table>
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<th>Group</th>
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<th>No. of Mice</th>
<th>Gastric Acid Output (mg/kg)</th>
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<td>Control</td>
<td>5</td>
<td>1.00 ± 0.12</td>
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<tr>
<td>Pranlukast</td>
<td>3</td>
<td>0.88 ± 0.20</td>
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<tr>
<td>TMK688</td>
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<td>1.01 ± 0.50</td>
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Fig. 7. A, mucosal expression of CysLT1R mRNA in the mouse stomach given indomethacin alone or subjected to I/R treatment in the absence or presence of indomethacin. Indomethacin (IM; 5 mg/kg) was given subcutaneously 30 min before ischemia. The expression of CysLT1R mRNA was analyzed by RT-PCR 2 h after indomethacin alone or 1 h after reperfusion. B, densitometric quantitation was performed with ImageJ software, and the results are expressed as the ratio of CysLT1R to GAPDH. Data are presented as the mean ± S.E. for five mice. Significant difference at #, P < 0.05 from sham and *, from indomethacin alone.

Fig. 8. A, mucosal expression of 5-LOX mRNA in the mouse stomach given indomethacin alone or subjected to I/R treatment in the absence or presence of indomethacin. Indomethacin (IM; 5 mg/kg) was given subcutaneously 30 min before ischemia. The expression of 5-LOX mRNA was analyzed by RT-PCR 2 h after indomethacin alone or 1 h after reperfusion. B, densitometric quantitation was performed with ImageJ software, and the results are expressed as the ratio of 5-LOX to GAPDH. Data are presented as the mean ± S.E. for five mice. Significant difference at #, P < 0.05 from sham and *, from control. 

partly, by the suppression of these inflammatory responses such as neutrophil infiltration, through the blockade of CysLT1R. Anderson et al. (2009) reported that montelukast, a CysLT1R antagonist, inhibits the proinflammatory action of neutrophils in vitro. In the present study, we confirmed the neutrophil infiltration in the stomach during I/R treatment, as represented by a marked increase of MPO activity, and further observed that pranlukast as well as TMK688 attenuated the increase of MPO activity after I/R treatment. These all results strongly suggest the involvement of CysLTs/CysLT1R in the pathogenesis of I/R-induced gastric injury. We also found that the expression of CysLT1R mRNA in the gastric mucosa was significantly increased under I/R conditions, although the mucosal CysLT content remained unchanged before and after I/R treatment. In other organs such as brain and kidney, the expression of CysLT1R mRNA was reportedly up-regulated by ischemia alone or I/R treatment (Fang et al., 2007; Matsuyama et al., 2008). It is assumed that the increased sensitivity to CysLTs in the mouse stomach under I/R conditions is, at least in part, accounted for by the up-regulation of CysLT1R expression, although I/R did not increase CysLT production in the stomach. By contrast, indomethacin alone slightly up-regulated the CysLT1R expression but did not further enhance the increased expression caused by I/R, excluding a possibility of the up-regulation of CysLT1R responsible for the aggravating mechanism by indomethacin of the I/R-induced gastric injury.

We reported previously that I/R caused gastric lesions with the up-regulation of COX-2 expression and that the damage was significantly aggravated by indomethacin as well as the selective COX-2 inhibitor rofecoxib but not the selective COX-1 inhibitor SC-560, suggesting the involvement of COX-2/PGs in mucosal defense during I/R (Kotani et al., 2006). Because I/R injury is a neutrophil-dependent response (Zimmerman and Granger, 1990), it is assumed that selective COX-2 inhibitors promote the adherence of leukocyte to the vascular endothelium during I/R, thereby resulting in aggravation of the lesions in the stomach (Muscarà et al., 2000). Similar results were reported by Maricic et al. (1999) who showed that I/R-induced gastric damage was aggravated by the administration of selective COX-2 inhibitors such as NS-398 and 5,5-dimethyl-3-(3-fluorophenyl)-4-(4-methylsulfonyl)phenyl-2(5H)-furanone. Because several studies showed that CysLT production in the stomach or the small intestine was increased by pretreatment with indomethacin (Wallace et al., 1990; Nishio et al., 2007), it is possible that the metabolism of arachidonic acid leads to the production of LTs via 5-LOX when another pathway to PGs is blocked by COX inhibition. In the present study, we observed that both CysLT production and 5-LOX mRNA expression in the stomach were significantly increased in the presence of indomethacin under I/R conditions. It should also be noted that indomethacin alone, but not I/R, markedly up-regulated the expression of 5-LOX in the gastric mucosa. Moreover, the coadministration of TMK688, a 5-LOX inhibitor, markedly suppressed the increase of CysLT production and the aggravation of I/R-induced gastric lesions under indomethacin pretreatment, without any effect on the expression of CysLT1R. These results together with previous findings (Kotani et al., 2006) suggest that the aggravation by indomethacin of I/R-induced gastric damage is brought about by not only a decrease of PG production but also an increase of 5-LOX expression/CysLT production. At present, however, the mechanism for how indomethacin up-regulates 5-LOX expression in the stomach remains unknown.

Although a selective COX-2 inhibitor, rofecoxib, increased the severity of I/R-induced gastric injury, similar to indomethacin (Kotani et al., 2006), the mechanisms for aggravation seem to differ in these cases. The worsening effect of these two agents was significantly prevented by the coadministration of prostacyclin (Kotani et al., 2006). We recently found that the aggravation by rofecoxib, but not indomethacin, of I/R-induced gastric injury was significantly abrogated by ozagrel, the inhibitor of thromboxane A2 (TXA2) synthesis as well as seratrodast, the TXA2 receptor antagonist (Nakamori et al., 2009). These results suggest that the worsening effect of rofecoxib may be partly accounted for by the imbalance of TXA2/prostacyclin ratio in the stomach and is apparently different from that of indomethacin, which may be related to the increase of CysLT production and 5-LOX expression, in addition to PG deficiency.

It has been reported that gastric acid secretion was substantially decreased after ischemia and remained decreased for several hours even after reperfusion (Takeuchi et al., 1986; Nakamoto et al., 1998). However, Kitano et al. (1997) reported that cimetidine, a histamine H2 receptor antagonist, had a protective effect against I/R-induced gastric damage through the suppression of acid secretion. In a preliminary study, we observed that lansoprazole, a proton pump inhibitor, also significantly reduced the severity of I/R-induced gastric damage in mice, suggesting the partial involvement of gastric acid in the pathogenesis of these lesions. In the present study, however, because basal gastric acid secretion in mice was significantly affected by neither pranlukast nor TMK688, the protective effects of these agents against I/R-induced gastric ulceration were accounted for by actions other than the inhibition of acid secretion. These results support an idea that the prophylactic effects of pranlukast or TMK688 may be brought about by the suppression of the inflammatory responses such as neutrophil infiltration and cytokine production during I/R, through the inhibition of CysLT production.

Given the findings of the present study, we concluded that I/R treatment up-regulated the expression of CysLT1R in the stomach and that CysLTs play a crucial role in the pathogenesis of I/R-induced gastric lesions through the activation of CysLT1R. In addition, the aggravation by indomethacin of I/R-induced gastric injury may be brought about by the increase of CysLT production as well as the up-regulation of 5-LOX expression, in addition to the decreased PG production. The present study cannot exclude a possibility that CysLT1R antagonist may play a role in the gastric ulcerogenic response to I/R, in addition to CysLT1R. Further study using a selective CysLT1R antagonist is needed to clarify this point.

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