Dual action of prostaglandin E₂ on gastric acid secretion through different EP-receptor subtypes in the rat

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Kato, Shinichi, Eitaro Aihara, Katsuhide Yoshii, and Koji Takeuchi. Dual action of prostaglandin E₂ on gastric acid secretion through different EP-receptor subtypes in the rat. Am J Physiol Gastrointest Liver Physiol 289: G64–G69, 2005; doi:10.1152/ajpgi.00397.2004.—We examined the role of prostaglandin E (EP) receptor subtypes in the regulation of gastric acid secretion in the rat. Under urethane anesthesia, the stomach was superfused with saline, and the acid secretion was determined at pH 7.0 by adding 50 mM NaOH. The acid secretion was stimulated by intravenous infusion of histamine or pentagastrin. Various EP agonists were administered intravenously, whereas EP antagonists were given subcutaneously 30 min or intravenously 10 min before EP agonists. PGE₂ suppressed the acid secretion stimulated by either histamine or pentagastrin in a dose-dependent manner. The acid inhibitory effect of PGE₂ was mimicked by sulprostone (EP₁/EP₃ agonist) but not butaprost (EP₂ agonist) or AE₁–329 (EP₄ agonist). The inhibitory effect of sulprostone, which was not affected by ONO-8711 (EP₁ antagonist), was more potent against pentagastrin (50% inhibition dose: 3.6 µg/kg) than histamine-stimulated acid secretion (50% inhibition dose: 18.0 µg/kg). Pentagastrin increased the luminal release of histamine, and this response was also inhibited by sulprostone. On the other hand, AE₁–329 (EP₄ agonist) stimulated the acid secretion in vagotomized animals with a significant increase in luminal histamine. This effect of AE₁–329 was totally abolished by cimetidine as well as AE₃–208 (EP₃ antagonist). These results suggest that PGE₂ has a dual effect on acid secretion: inhibition mediated by EP₁ receptors and stimulation through EP₄ receptors. The former effect may be brought about by suppression at both parietal and enterochromaffin-like cells, whereas the latter effect may be mediated by histamine released from enterochromaffin-like cells.

Histamine; pentagastrin; enterochromaffin-like cells

PROSTAGLANDINS (PG) ARE PRODUCED from arachidonic acid by two isoforms of cyclooxygenase (COX-1 and COX-2) in the mucosa throughout the gastrointestinal tract (9, 26). The E series of PGs are especially important, having roles in the regulation of various physiological functions in the stomach, including the secretion of acid, pepsinogen, and mucus, as well as motility (6, 9).

It is generally believed that PGE₂ negatively regulates gastric acid secretion (22). There are many reports of PGE suppressing gastric acid secretion in experimental animals (12, 13, 38) and humans (2). Similar observations have also been shown in vitro using isolated amphibian stomach (37) and canine parietal cells (27). In contrast, one of the present authors previously showed, using isolated amphibian stomach, that 16,16-dimethyl-PGE₂, a stable analog of PGE₂, stimulated acid secretion at high concentrations, through the release of endogenous histamine, while it suppressed acid secretion at low concentrations (31). Sernka and Caplan (25) showed, in the isolated rat gastric mucosa, that PGE₂ stimulated oxygen consumption and H⁺ transport, indicating the activation of parietal cells. In addition, Nylander et al. (17) reported that PGE₂ increased the release of endogenous histamine, despite inhibiting the effect of histamine on the parietal cells. It is well recognized that histamine released from enterochromaffin-like (ECL) cells plays a pivotal role in the regulation of acid secretion. Thus the influence of PGE₂ on acid secretion is complicated and is still not fully understood.

The receptors activated by PGE₂ are pharmacologically subdivided into four subtypes, EP₁−EP₄ (4). The distribution of these receptors is considered to explain the multiple effects of PGE₂ in various tissues, including the gastrointestinal tract. It is possible that a dual effect of PGE₂ on acid secretion appears through different EP receptor subtypes.

In the present study, we reexamined the effect of PGE₂ on gastric acid secretion, especially in relation to EP-receptor subtypes, using various EP-receptor agonists and antagonists in rats.

METHODS

Animals. Male Sprague-Dawley rats (220–250 g, Charles River, Atsugi, Japan), kept in individual cages with raised mesh bottoms, were deprived of food but allowed free access to water for 18 h before the experiments. All studies were carried out under urethane anesthesia (1.25 g/kg ip), using five to six rats per group. All experimental procedures employed in the present study were approved by the Experimental Animal Research Committee of the Kyoto Pharmaceutical University.

Measurement of gastric acid secretion. The trachea was cannulated to ensure a patent airway. The abdomen was incised, the stomach was exposed, and two polyethylene tubes were inserted into the stomach through the forestomach and the pyloric ring. The stomach was then perfused using a peristaltic pump (AC-2110, ATTO, Tokyo, Japan) at a flow rate of 1 ml/min, with saline that was gassed with 100% O₂ to avoid the influence of CO₂ on pH, heated at 37°C, and kept in a reservoir (100 ml). The perfusate was continuously titrated using a pH-stat method with an automatic titrator (AUT-501, TOA, Tokyo, Japan) at pH 7.0 by adding 50 mM NaOH to the reservoir for the measurement of acid secretion. Gastric acid secretion was expressed in two ways, as an acid output every 10 min (µeq/10 min) and net acid output for 1 h (∆µeq/h). The net gastric acid output was calculated by subtracting the mean basal value (mean of three points obtained before the administration of EP agonist) from each value and by summation of these values obtained for 1 h after the administration. Body temperature was kept around 36 ± 1°C using a heating lamp.

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Allowing a 30- to 40-min stabilization of basal secretion, gastric acid secretion was stimulated by intravenous (IV) infusion of pentagastrin (100 μg·kg\(^{-1}·h^{-1}\)) or histamine (4 mg·kg\(^{-1}·h^{-1}\)) at the submaximal dose via a tail vein. After the acid secretion stimulated by pentagastrin or histamine had reached a plateau, various EP agonists, PGE\(_2\) (EP1/EP2, PGE\(_2\) agonist: 0.1–1 mg/kg), sulprostone (EP3 agonist: 1–30 μg/kg), butaprost (EP3 agonist: 3 mg/kg), and ONO-AE1–329 (EP1 agonist: 10 μg/kg), were administered IV via a tail vein as a single injection. EP antagonists ONO-8711 (EP1 antagonist: 30 mg/kg) and ONO-AE3–208 (EP4 antagonist: 1 mg/kg) were administered subcutaneously 30 min or IV 10 min before the administration of sulprostone (10 μg/kg), respectively. The 50% inhibition dose (ID\(_{50}\)) of PGE\(_2\) and sulprostone against the acid secretion stimulated by pentagastrin or histamine was calculated from values of the maximal inhibition observed after the injection of these agents.

In a separate experiment, we also examined the effect of various EP agonists on basal acid secretion in normal and vagotomized rats. Vagotomy was performed bilaterally at the cervical portion 1 h before the onset of the experiment. At least 1 h after basal acid secretion had stabilized, various EP agonists, such as PGE\(_2\) (1 mg/kg), sulprostone (30 μg/kg), butaprost (3 μg/kg), and ONO-AE1–329 (1–10 μg/kg), were administered IV via a tail vein as a single injection.

**Preparation of drugs.** Drugs used were urethane (Tokyo Kasei, Tokyo, Japan), pentagastrin (Sigma Chemicals, St. Louis, MO), histamine dihydrochloride (Nacali Tesque, Kyoto, Japan), PGE\(_2\), sulprostone, butaprost (Cayman Chemical, Ann Arbor, MI), ONO-AE1–329, ONO-8711, and ONO-AE3–208 (kindly supplied by Ono Pharmaceutical, Osaka, Japan). Histamine was dissolved in saline. Pentagastrin was first dissolved in 0.05% ammonia solution and then diluted with saline to the desired concentration. ONO-AE3–208 was first dissolved in 1 M NaOH and then diluted with saline to the desired concentration, and ONO-8711 was suspended in a 0.5% carboxymethylcellulose (Nacali Tesque) solution. Each drug was prepared immediately before use and administered IV in a volume of 1 ml/kg, subcutaneously in a volume of 5 ml/kg, and IV infusion in a volume of 5 ml·kg\(^{-1}·h^{-1}\).

**Statistical analysis.** Data are presented as the means ± SE from five to six rats per group. Statistical analyses were performed using a two-tailed Student’s \(t\)-test and Dunnett’s multiple-comparison test, and values of \(P < 0.05\) were regarded as significant.

**RESULTS**

Effects of various EP agonists on pentagastrin-stimulated acid secretion. IV infusion of pentagastrin (100 μg·kg\(^{-1}·h^{-1}\)) produced a progressive increase in acid secretion, with a plateau value reached within 1 h after the onset of the infusion, and the acid secretion was 19.0 ± 1.5 μeq/10 min. The acid secretory response induced by pentagastrin was significantly attenuated by a single IV injection of PGE\(_2\) (1 mg/kg) and sulprostone (10 μg/kg) but not butaprost (3 mg/kg) or AE1–329 (10 μg/kg) (Fig. 1A). PGE\(_2\) (0.1, 0.3, and 3 mg/kg) dose-dependently suppressed the acid secretion, and a significant effect was obtained even at 0.1 mg/kg (Fig. 1B). A dose-dependent suppression of the acid output was also observed by sulprostone (1, 3, and 10 μg/kg), and the effect was significant at all doses. The ID\(_{50}\) values (95% confidence interval) of PGE\(_2\) and sulprostone determined from the maximal inhibition were 0.6 (0.1–1.4) mg/kg and 3.6 (1.5–9.1) μg/kg, respectively. On the other hand, the inhibitory effect of sulprostone (10 μg/kg) on pentagastrin-stimulated acid secretion was not affected by prior subcutaneous administration of ONO-8711 (EP1 antagonist; 30 mg/kg), and the net acid output was \(-72.1 ± 1.8\) μeq/h, the value being almost equivalent to that of control animals (\(-81.7 ± 4.7\) μeq/h) (Fig. 1B).

Effects of various EP agonists on histamine-stimulated acid secretion. Gastric acid secretion was also stimulated by IV infusion of histamine (4 mg·kg\(^{-1}·h^{-1}\)), reaching a plateau value 1 h later, and the total acid out was 27.0 ± 2.2 μeq/10 min. Both PGE\(_2\) (1 mg/kg) and sulprostone (10 μg/kg) significantly attenuated the acid secretory response induced by histamine, whereas neither butaprost (3 mg/kg) nor AE1–329 (10 μg/kg) had any effect (Fig. 2A). As shown in Fig. 2B, PGE\(_2\) (0.1, 0.3, and 1 mg/kg) decreased the net acid output in a dose-dependent manner, and a significant effect was obtained at all doses. Sulprostone (1, 3, and 10 μg/kg) also produced a dose-dependent suppression of the histamine-induced acid secretion, and the effect was significant at all doses used. The
ID₅₀ values (95% confidence interval) of PGE₂ and sulprostone against the histamine-induced acid secretion were 1.3 (0.6–2.8) mg/kg and 18.0 (11.7–27.7) µg/kg, respectively, both of which were greater than those for the pentagastrin-stimulated acid secretion.

Effects of sulprostone on luminal release of histamine induced by pentagastrin. The amount of luminal histamine release was 4.6 ± 2.9 pg/30 min (Fig. 3). IV infusion of pentagastrin (100 µg·kg⁻¹·h⁻¹) increased the luminal release of histamine, the value being 29.5 ± 3.5 pg at 30- to 60-min interval after the onset of infusion. This response was inhibited by IV administration of PGE₂ (1 mg/kg) and sulprostone (10 µg/kg), and the effect was significant at 30- to 60-min interval or 60- to 90-min interval, respectively; the inhibition by PGE₂ was 57.9%, whereas that by sulprostone was 52.1%.

Effects of various EP agonists on basal acid secretion in normal and vagotomized rats. Basal acid secretion in normal rats was 5.3 ± 0.6 µeq/10 min. The rate of basal secretion was significantly decreased by IV administration of PGE₂ (1 mg/kg) but not butaprost (3 µg/kg) (Fig. 4). The EP₄ agonist AE1–329 (10 µg/kg) given IV showed a slight tendency to increase basal acid secretion, although this effect was not statistically significant compared with the control group.

Because basal acid secretion depends largely on the vagus nerves, it is possible that any stimulatory effect of the EP₄ agonist is underestimated. Then we further examined the effects of various EP agonists on acid secretion in vagotomized stomachs, where the basal level of acid secretion was low (2.8 ± 0.4 µeq/10 min). IV administration of both PGE₂ (1 mg/kg) and sulprostone (10 µg/kg) caused a slight but significant decrease in the acid secretion in vagotomized rats, whereas AE1–329, the EP₄ agonist (10 µg/kg), apparently increased the acid secretion (Fig. 5A). The net acid output for 1 h after the administration of AE1–329 (1, 3, and 10 µg/kg) was 4.0 ± 1.4, 8.4 ± 2.0, and 10.2 ± 2.3 µeq/1 h, respectively, and a significant increase was observed even at 1 µg/kg (Fig. 5B). The acid stimulatory effect of AE1–329 (10 µg/kg) was totally abolished by prior administration of AE3–208 (EP₄ antagonist; 10 µg/kg) or cimetidine (200 µg/kg), the inhibition being 117.7 and 97.6%, respectively.

Effect of AE1–329 on pentagastrin-induced histamine release in vagotomized stomachs. The amount of luminal histamine release in the vagotomized stomach was 3.2 ± 0.2 pg/30 min (Fig. 6). IV administration of PGE₂ (1 mg/kg) slightly suppressed the release of histamine to 2.7 ± 0.1 pg at 30- to 60-min intervals after the injection, whereas AE1–329 (10 µg/kg), given IV, significantly enhanced the luminal release of histamine to 5.8 ± 0.5 pg for the first 30 min.

DISCUSSION

Exogenously administered PGE and its analogs have been reported to suppress gastric acid secretion in rats (12, 13) and dogs (38) as well as humans (2). Way and Durbin (37) showed that PGE₁ inhibited acid secretion stimulated by histamine but not by cAMP in the isolated amphibian fundic mucosa. Soll (27) demonstrated, using isolated canine parietal cells, that PGE₂ directly suppressed the parietal cell activity stimulated by histamine but not by carbachol or gastrin. These studies in vitro suggest that PGE directly suppresses the activity of
parietal cells, especially those stimulated by histamine. In the present study, we observed that PGE2 given IV dose dependently suppressed acid secretion stimulated by not only histamine but also pentagastrin in anesthetized rats. Because gastrin stimulates acid secretion mediated by endogenous histamine released from ECL cells (1, 7, 8, 20, 23, 36), it is assumed that the inhibitory effect of PGE2 on acid secretion is specific for the histamine-induced response of the parietal cell.

We further observed that the inhibitory effect of PGE2 on acid secretion was mimicked by the EP1/EP3 agonist sulprostone but not the EP2 agonist butaprost or the EP4 agonist AE1–329. In addition, ONO-8711, a specific EP1 antagonist, did not affect the inhibitory effect of sulprostone on pentagastrin-stimulated acid secretion. Our laboratory previously showed that ONO-8711 at the dose used in the present study totally abolished adaptive gastroprotection induced by mild irritants, the phenomenon mediated by EP1 receptors (34). These findings suggest that the inhibitory effect of PGE2 on acid secretion is mainly mediated by EP3 receptors. Yokotani et al. (39) reported that the activation of central EP3 receptors inhibited vagally mediated gastric acid secretion through the increase of central sympathetic outflow in rats. Sympathetic neurons functionally antagonize the actions mediated by the vagal-cholinergic system, by inhibiting the release of acetylcholine. We observed, however, in the present study, that IV injection of PGE2 and sulprostone significantly suppressed acid secretion, even in vagotomized rats, suggesting the inhibitory effect through EP3 receptors on acid secretion, independent of vagal innervation. Because we did not examine the effect of sympathectomy on the acid secretory changes caused by PGE2 in the present study, a possibility cannot be totally excluded that the inhibitory effect of PGE2 originates centrally, in addition to that which occurred peripherally. We also found that the inhibitory effects of PGE2 and sulprostone were much more potent when acid secretion was stimulated by pentagastrin rather than histamine. These results may be related to the different mechanisms in the process of acid secretion induced by these secretagogues. Several studies showed that PGs inhibited histamine release from isolated perfused stomach (24), isolated canine oxyntic mucosal cells (27), and isolated rat ECL cells (19). In the present study, sulprostone significantly

Fig. 4. Effects of various EP agonists on basal gastric acid secretion in rats. PGE2 (1 mg/kg), butaprost (3 mg/kg), and AE1–329 (10 µg/kg) were administered intravenously as a single injection. A: values are presented as the means ± SE of values determined every 10 min from 5–6 rats. B: values represent the net gastric acid output obtained for 1 h after the injection of EP agonist and are presented as the means ± SE from 5–6 rats. *Statistically significant difference from control (vehicle alone), at P < 0.05.

Fig. 5. Effects of various EP agonists on gastric acid secretion in vagotomized rats. Vagotomy was performed acutely at the cervical portion 1 h before the injection of EP agonists. PGE2 (1 mg/kg), sulprostone (30 µg/kg), butaprost (3 mg/kg), and AE1–329 (1–10 µg/kg) were administered intravenously as a single injection. AE1–208 (EP4 antagonist: 10 µg/kg) was administered intravenously 10 min before, whereas cimetidine (200 mg/kg) was administered subcutaneously 30 min before the injection of AE1–329. A: values are presented as the means ± SE of values determined every 10 min from 5–6 rats. B: values represent the net gastric acid output obtained for 1 h after the injection of EP agonist and are presented as the means ± SE from 5–6 rats. Statistically significant difference at P < 0.05; *from control (vehicle alone); #from values treated with AE1-329 (10 µg/kg).
the isolated rat gastric mucosa, that PGE2 stimulated oxygen
consumption and H⁺ transport, indicating an enhancement of parietal cell activity by this agent. In contrast, Nylander et al. (17) reported that PGE has two opposing effects: liberation of endogenous histamine and inhibition of the histamine action on the parietal cell. In the present study, we observed that basal acid secretion was significantly suppressed by PGE2 but slightly augmented by AE1–329, the EP₄ agonist. Because basal acid secretion depends largely on the vagus nerves, it is possible that the acid stimulatory effect of the EP₄ agonist is underestimated. As expected, we found that the acid secretion was dose dependently enhanced by AE1–329 in the vagotomized stomach, where the basal level of secretion was very low, and this effect was totally abolished by cimetidine as well as AE2–208, the specific EP₁ antagonist. Furthermore, AE1–329 significantly increased the release of luminal histamine in the vagotomized stomach. These results strongly suggest that the stimulatory effect of PGE₂ on acid secretion is brought about by the release of endogenous histamine from ECL cells, the process being mediated by EP₃ receptors. However, the stimulatory effect of PGE₂ through EP₄ receptors seems not to be so potent, as the EP₄ agonist did not significantly increase basal acid secretion in normal rats and as PGE₂ itself inhibited basal acid secretion mediated by the activation of EP₃ receptors. It is assumed that the stimulatory effect of PGE₂ through EP₄ receptors is overcome by the inhibitory effect mediated by EP₁ receptors and that the former effect is predominant. Anyhow, the present results confirmed the stimulatory effect of PGE₂ observed in previous studies in vitro, where basal secretion was made scanty by excluding extrinsic nerves, as in vagotomized stomachs used in the present study.

Ding et al. (5) showed, using Northern blot analysis, that both the EP₃- and EP₄-receptor genes were mainly expressed in the parietal cell. The EP₃ receptor has at least four splicing variants coupled with different signaling pathways (14). The EP₃A receptor is linked to the activation of Gₛ protein, resulting in a suppression of intracellular cAMP levels, whereas EP₃B and EP₃C are coupled with the activation of Gₛ protein, resulting in an increase of intracellular cAMP. In addition, activation of the EP₃D receptor causes an elevation of intracellular Ca²⁺ by stimulating Gₛ protein. It has also been reported that PGE₂ and its analog inhibited acid secretion as well as cAMP production stimulated by histamine in parietal cells (27, 35). It is likely that the inhibitory effect of PGE₂ on acid secretion is mediated by activation of EP₃, especially EP₃A receptors through inhibition of intracellular cAMP in the parietal cell. On the other hand, Naribayashi-Inoue et al. (15) reported that EP₂ and EP₃ receptors were found on ECL carcinid tumor cells of Mastomys, African rodents. They also showed that PGE₂ enhanced the generation of cAMP through EP₂ receptors while inhibiting the cAMP production induced by forskolin through EP₃ receptors. Thus the EP₃A receptor may also be involved in the inhibitory effect of PGE₂ on histamine release from ECL cells. In the present study, however, the EP₂ agonist butaprost had no influence on acid secretion, and the EP₄ agonist stimulated acid secretion through the release of histamine from ECL cells in vagotomized rats. The reason for these different results remains unclear, yet the difference may be due to different experimental conditions, such as animal species.

The physiological implication of the present findings in the regulation of acid secretion remains unknown. Our laboratory previously reported that gastric acid secretion was decreased in the damaged stomach following the barrier disruption (16, 30). This response is mediated by enhanced release of PGE₂ and plays a role in maintaining the microclimate for restitution of the injured tissue. We also reported that damage in the stomach enhances the acid stimulatory pathway, in addition to the PG-dependent inhibitory pathway, although the latter effect normally overcomes the former, resulting in a decrease of acid secretion (32). This stimulatory acid response is mediated by release of endogenous histamine, the process being also modified by a PG-dependent mechanism (33). It is assumed that

Fig. 6. Effects of PGE₂ and AE1–329 on luminal histamine release in vagotomized rat stomachs. PGE₂ (1 mg/kg) or AE1–329 (10 µg/kg) was administered intravenously as a single injection. Vagotomy was performed acutely at the cervical portion 1 h before the injection of EP agonists. Values are presented as the means ± SE of values determined every 30 min from 5 rats. *Statistically significant difference from the corresponding basal values (before the injection of PGE₂ or AE1–329), at P < 0.05.
endogenous PGs may have a dual role in the regulation of acid secretion in the damaged stomach. The stimulatory effect mediated by EP4 receptors, although not so potent, may contribute to prevent the excessive inhibition of acid secretion caused by activation of EP3 receptors. Certainly, there is a possibility that the histamine release from ECL cells mediated by EP4 receptors may serve another function than stimulation of acid secretion.

Taken together, it is concluded that PGE2 has a dual effect on the regulation of acid secretion: inhibition mediated by EP3 receptors and stimulation through EP4 receptors. The former effect may be brought about by suppression at both parietal and ECL cells, whereas the latter effect may be mediated by histamine release from ECL cells.

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