NHE3 inhibition activates duodenal bicarbonate secretion in the rat

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Submitted 21 February 2003; accepted in final form 18 July 2003

DEPL. TITR. S3226

anion transporter function.

Because NHE3 inhibition-increased DBS was inhibited by an anion channel inhibitor and because reciprocal CFTR regulation has been shown to make concentrated stock solutions. 10, 21, 34). In the colonic surface mucosa, an apical NHE3 plays a key absorptive role for Na+, concomitant with H+ excretion (31). In contrast, NHE2 may promote Na+ absorption from colonic crypts (12), whereas playing only a minor role in overall small intestinal electrolyte transport (18, 29).

In a recently published clinical study (36), inhibition of NHE2 and NHE3 by amiloride increased DBS. This increased DBS was thought to result from decreased NHE2- and NHE3-mediated H+ secretion into the lumen, increasing the amount of measured titratable alkalinity. Although it is plausible that an apparent rather than a true increase of DBS was measured, the constraints imposed by clinical studies prevented differentiation of measured titratable alkalinity. Although it is plausible that an apparent rather than a true increase of DBS was measured, the constraints imposed by clinical studies prevented differentiation of measured titratable alkalinity. Although it is plausible that an apparent rather than a true increase of DBS was measured, the constraints imposed by clinical studies prevented differentiation of measured titratable alkalinity. Because NHE3 inhibition increased DBS was inhibited by an anion channel inhibitor and because reciprocal CFTR regulation has been previously shown between NHE3 and apical membrane anion transporters, we speculate that NHE3 inhibition increased DBS by altering anion transporter function.

epithelial cells; cystic fibrosis transmembrane conductance regulator; back titration; S3226

DUODENAL EPITHELIAL BICARBONATE secretion (DBS) is one of the most important mechanisms by which the duodenum is protected from the injurious effects of secreted gastric acid (6, 16). DBS is regulated by humoral factors such as PGE2, VIP, glucagon, gastric inhibitory peptide, and the enteric nervous system (6). These factors promote cAMP production, which stimulates the cystic fibrosis transmembrane conductance regulator (CFTR), an apical anion channel (19, 20), and the basolateral Na+/HCO3− cotransporter (NBC1), an HCO3− transporter activation, or intracellular HCO3− formation by carbonic anhydrase was not involved. Because NHE3 inhibition increased DBS was inhibited by an anion channel inhibitor and because reciprocal CFTR regulation has been previously shown between NHE3 and apical membrane anion transporters, we speculate that NHE3 inhibition increased DBS by altering anion transporter function.

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the abdomen was incised, and both stomach and duodenum were exposed. A duodenal loop (2 cm) was made distal to the pyloric ring. To prevent contamination of the perfusate from bile-pancreatic juice, the pancreaticobiliary duct was ligated just proximal to its insertion into the duodenal wall.

**pH-stat method.** The resultant closed proximal duodenal loop was perfused with prewarmed saline by using a peristaltic pump at 1 ml/min. Input and effluent of duodenal loop were circulated through a reservoir, in which the perfusate was bubbled with 100% O2 gas (3, 4). The pH of the perfusate was kept at pH 7.0 with a pH-stat (models PHM290 and ABU901; Radiometer Analytical, Lyon, France). For back titration, the amount of 10 mM HCl added to keep the pH of the perfusate at 7.0 per time period was considered equivalent to the duodenal HCO3- secretory rate. After reaching stability for at least 15 min, S3226 (1 and 10 μM) was added to the perfusate.

**CO2 measurements.** Total dissolved CO2 was measured by the CO2 electrode gas sensing electrode (model 950200; Thermo Orion, MA) connected to a pH meter (model PHM 62; Radiometer, Copenhagen, Denmark) (3, 4). Duodenal loops were prepared and perfused with 20 mM HEPES containing saline (pH 7.0) at a rate of 1 ml/min as described above, with effluent collected every 5 min. We then added 0.5 ml of 1 M citrate buffer (pH 4.5) to the sample (5 ml) to convert free HCO3- to CO2, followed by measurement of electrode potential with the CO2 electrode. Total dissolved CO2 concentration ([CO2]t) was calculated according to a calibration curve by using freshly prepared 0.1, 1, and 10 mM Na+/HCO3- solutions as standards, which generate 0.1, 1, and 10 mM [CO2]t, respectively (3). After reaching stability for at least 15 min as well as the pH-stat method, S1611, S3226, or DMA was added to the perfusate to examine the effects of these compounds.

To inhibit NHE2, 50 μM DMA was added to the perfusate, and to inhibit NHE3, 3 mM DMA or 1–10 μM S1611 or S3226 (37) were added to the perfusates.

We also studied DBS by using Na+-free conditions with 20 mM HEPES solution containing NMDG, pH 7.0. The duodenal loop was first perfused with 20 mM HEPES in saline; after CO2 measurements reached stability for at least 15 min, we then perfused with NMDG. CO2 measurements were carried out for at least an additional 45 min or until CO2 measurements reached a new plateau.

In some cases, the anion channel inhibitor NPPB (0.1 and 0.3 mM) was added to inhibit CFTR function. Moreover, we used the anion transport inhibitor DIDS (0.5 mM) or the permeant carbonic anhydrase inhibitor methazolamide (1 mM), both of which inhibit acid-stimulated DBS by inhibiting HCO3- entry into or HCO3- formation within the cell, respectively (4). In some cases, the nonselective cyclooxygenase inhibitor indomethacin (0.1 μM) was added to the perfusate before the addition of S3226.

**Measurement of pH.**

In vivo microscopic preparation. An in vivo microfluorometric technique, described in detail elsewhere (5) was used to measure pH, in rat duodenal epithelial cells. After urethane (1.25 g/kg) anesthesia, the rat was placed supine on a plastic stage. Body temperature was maintained at 36–37 °C by a heating pad, and rectal temperature was monitored throughout the experiment. A tracheal cannula was inserted, and warmed saline was continuously infused through the left femoral vein at a rate of 1.08 ml/h by using a Harvard infusion pump. Arterial blood pressure was monitored via a catheter placed in the left femoral artery. The abdomen was opened via a 3-cm midline incision, and the duodenum was exposed. The pylorus was tightly ligated to prevent gastric juice from entering into the proximal duodenum, and the duodenum was temporarily closed with a nylon suture proximal to the ligament of Treitz before filling the duodenal loop with 0.5 ml saline prewarmed at 37°C. The anterior wall of the duodenum was incised distal to the pylorus to just proximal to the papilla of Vater papilla by using a miniature electrocautery to prevent bile-pancreatic juice from contaminating to the observed duodenal mucosa. A concave stainless steel disk (16 mm diameter and 1–2 mm deep with a 3-mm central aperture) was fixed watertight on the mucosal surface with a silicone plastic adherent (Silly Putty; Binney & Smith, Easton, PA). The serosal surface of the duodenum was supported with a rigid rod. A thin plastic coverslip was fixed to the disk with the silicone adherent to permit closed perfusion with solutions (total volume, 50 μl; rate, 0.25 ml/min) by using a Harvard infusion pump. Two polyethylene-50 perfusion lines were inserted into the chamber so as to enable rapid changes of perfusate (e.g., pH 7.0 to 2.2). The exposed mucosa was incubated with 50 μl Krebs solution (pH 7.0) containing 10 μM 2’,7’-bis(2-carboxyethyl)-5(6)-carboxyfluorescein/AM for 15 min to load the duodenal epithelial cells before starting the experiment.

**Image Analysis**

Fluorescence of the microscopically observed chambered segment of duodenal mucosa at 515 nm emission was recorded with a cooled charge-coupled device video camera (Hamamatsu Orca-EN; Hamamatsu, Bridgewater, NJ). Fluorescence intensity of the selected area was measured by first capturing the image by using an Apple G4 microcomputer and digitized with area of interest defined, and intensity was measured by using image analyzer software (OpenLab; Improvision, Lexington, MA). The intensity of emitted fluorescence at 495 nm stimulation is pH dependent, whereas that at 450 nm is not. Therefore, 450 and 495 nm filters, narrow band-pass interference filters (Chroma, Brattleboro, VT) were used and each image was captured every 5 min. Readings were taken at 10 s before and after each time point. The paired readings needed to calculate a fluorescence ratio were thus taken at a maximum of 20 s apart. Image analysis was performed on the recorded images as follows: initially three small areas of a duodenal epithelium were selected at random and then followed throughout the experiment. In vitro calibration and background compensation using an aqueous solution containing 0.2 mM BCECF free acid were done as described previously (5, 24).

**Statistics**

Comparisons between groups were made by one-way ANOVA followed by Fisher’s least significant difference test. P < 0.05 was taken as significant.

![Fig. 1. Effects of 50 μM and 3 mM 5-(N,N-dimethyl)-amiloride (DMA) on duodenal bicarbonate secretion (DBS) measured by the CO2-sensitive electrode method. DMA was added to the perfusate after DBS was stabilized. In this and all subsequent figures, data are presented as the means ± SE from 6 rats. *Significantly different from control (P < 0.05).](http://www.ajpgi.org)
RESULTS

Effect of DMA on DBS

Initial experiments were conducted by using the concentration-dependent NHE inhibitor DMA, to selectively inhibit NHE isoforms. Basal DBS, as measured with the CO₂-sensitive electrode, was 0.08–0.10 μmol·min⁻¹·cm⁻¹. NHE2 activity was inhibited with 50 μM DMA perfused into the duodenal loop. As seen in Fig. 1, DBS was unchanged for at least for 1 h. In contrast, 3 mM DMA gradually increased DBS to ~0.15 μmol·min⁻¹·cm⁻¹ 30 min after the addition, with the increased secretion lasting for 60 min.

Fig. 2. Effects of S3226 on DBS measured by the CO₂-sensitive electrode method. A: perfusion with S3226 elevated DBS. B: withdrawal of S3226 did not affect DBS over the 40-min monitoring period, but injection of PGE₂ further raised secretion, indicating that S3226 did not affect the ability of the mucosa to secrete. C: when measured by the pH-stat method, results are qualitatively similar to secretion measured by CO₂ electrode.

Effects of S1611 and S3226 on DBS

To further confirm the role of NHE3 inhibition on DBS, we examined the effect of the more selective NHE3 inhibitors S1611 and S3226. Similar to the effects of 3 mM DMA, the addition of 1 or 10 μM of S3226 to the perfusate, which selectively inhibits NHE3 (37, 42), gradually and dose dependently increased DBS, as measured by the CO₂-sensitive electrode method. In particular, 10 μM S3226 significantly stimulated DBS within 10 min after the addition, reaching a peak of 1.5 times basal (Fig. 2A). After withdrawal of S3226, DBS remained elevated for 40 min and was further stimulated by the...
addition of PGE₂ (0.1 mg/kg iv; Fig. 2B). The effects of 1 or 10 μM S3226 on DBS were confirmed by using the pH-stat method. Basal DBS measured by the pH-stat method was ~0.05 μmol·min⁻¹·cm⁻¹. The addition of 1 or 10 μM S3226 to the circulating perfusate gradually and dose dependently increased DBS, reaching a peak of 1.5 times basal with 10 μM S3226 (Fig. 2C). We then examined the effect of S1611, which has a median inhibitory concentration (IC₅₀) for rat NHE3 greater than that of S3226 (0.69 vs. 0.23 μM) (44). Perfusion with 10 μM S1611 produced similar but less marked DBS stimulation than that of S3226, as measured by the CO₂-sensitive electrode method (Fig. 3).

Effects of NMDG on DBS

We then examined the role of perfusate Na substitution on DBS. Removal of Na from the perfusate inhibits NHE3 function by decreasing the Na available for exchange (34). As seen in Fig. 4, substitution of NMDG for Na in the perfusate rapidly increased DBS, as measured by the CO₂-sensitive electrode method, reaching a peak of 1.6 times basal within 15–20 min after initial perfusion with subsequent stabilization at a higher level.

Effects of Indomethacin, Methazolamide, DIDS, and NPPB on DBS

To further elucidate the mechanism by which inhibition of NHE3 increased DBS in rats, we examined the effects of several compounds on S3226-stimulated DBS, measured by using the CO₂-sensitive electrode method. Indomethacin (0.1 μM), which completely inhibits acid-induced DBS but did not affect PGE₂-stimulated DBS in rats (17), did not affect basal or S3226-induced DBS (Fig. 5). We then examined the effect of methazolamide, a permeant carbonic anhydrase inhibitor, on DBS. Methazolamide (1 mM) slightly decreased basal DBS from ~0.1 to ~0.08 μmol·min⁻¹·cm⁻¹ within 10–15 min after addition (Fig. 6A). This decreased DBS remained unchanged for 1 h. In the presence of methazolamide, 10 μM of S3226 increased DBS to a maximum value of 0.14 μmol·min⁻¹·cm⁻¹, somewhat less than the maximum value observed S3226 alone. When Δ increases (the area under the curve 60 min after S3226 addition, relative to the baseline recorded prior S3226 addition) were calculated, no significant difference between DBS after the addition of S3226 alone and methazolamide plus S3226 was observed (Fig. 6B). To examine the role of NBC1 on S3226-stimulated DBS, we tested the effect of 0.5 mM DIDS, which inhibits DBS presumably by inhibition of cellular HCO₃⁻ uptake (3, 4). DIDS (0.5 mM) after addition (Fig. 6A). This decreased DBS remained unchanged for 1 h. In the presence of methazolamide, 10 μM of S3226 increased DBS to a maximum value of 0.14 μmol·min⁻¹·cm⁻¹, somewhat less than the maximum value observed S3226 alone. When Δ increases (the area under the curve 60 min after S3226 addition, relative to the baseline recorded prior S3226 addition) were calculated, no significant difference between DBS after the addition of S3226 alone and methazolamide plus S3226 was observed (Fig. 6B). To examine the role of NBC1 on S3226-stimulated DBS, we tested the effect of 0.5 mM DIDS, which inhibits DBS presumably by inhibition of cellular HCO₃⁻ uptake (3, 4). DIDS (0.5 mM)
slightly increased basal DBS within 5–10 min after addition, after which DBS was unchanged. The subsequent addition of 10 μM S3226 increased DBS to a level not different from that observed with S3226 alone (Fig. 7A). DBS (Δ over baseline) for S3226 alone and DIDS plus S3226 were 0.51 ± 0.10 and 0.41 ± 0.14 μmol-60 min⁻¹-cm⁻¹, respectively, with no significant difference between the two groups (Fig. 7B). Lastly, to examine the role of the apical anion channel function on DBS, we examined the effect of NPPB on S3226-induced DBS. The addition of 0.1 or 0.3 mM NPPB did not affect basal DBS within 30 min after addition. Nevertheless, 0.1 mM NPPB significantly inhibited S3226-induced DBS 15–50 min after addition. Moreover, 0.3 mM NPPB almost completely inhibited S3226-induced DBS when both inhibitors were included in the perfusate (Fig. 8). Percent inhibitions, as calculated from Δ increases for 0.1 and 0.3 mM NPPB, were 49 and 78%, respectively.

Effect of S3226 on pHᵢ

In the last series of studies, we examined the effect of S3226 on pHᵢ, to determine whether S3226 decreased pHᵢ as a signal for DBS. Because NHE1 is a major regulator of pHᵢ and NHE3 might also be involved in pHᵢ regulation in duodenal epithelial cells (34), we hypothesized that NHE3 inhibition might decrease pHᵢ, serving as a signal for subsequent DBS. Our prior studies (4, 5) revealed that other stimuli of DBS, such as acid perfusion, lowered pHᵢ before the onset of DBS. As seen in Fig. 9, 10 μM S3226 had no effect on duodenal epithelial cells perfused in situ.
Indomethacin did not affect S3226-induced DBS, prostaglandin hormone analog induced DBS (40). Nevertheless, because induced DBS (26); and YM-14673, a thyrotropin-releasing hormone analog induced DBS (41); leukotriene C4/D4 antagonist L-649 nonselective cyclooxygenase inhibitor, inhibits basal and acid‐increased DBS, especially by S3226, is not well understood. The method thus detects only HCO3\(^{-}\) derived from extracellular sources. Extensive studies have confirmed the importance of this enzyme in HCO3\(^{-}\) secretion. Takeuchi et al. (41) examined the effect of acetazolamide, a classical carbonic anhydrase inhibitor on DBS in rats, and showed that it did not affect basal or PGE\(_2\)-stimulated DBS in rats. Mullem et al. (33) showed acetazolamide inhibited basal and VIP, PGE\(_2\), and glucagon-stimulated DBS in guinea pigs. Moreover, in an vitro study, Jacob et al. (22) reported 1 mM acetazolamide inhibited basal DBS in rabbits. In our experimental condition, 1 mM methazolamide, a more permeant analog of acetazolamide, decreased basal DBS by ~20% but did not affect the S3226-stimulated Δ increase of DBS. These results indicate that generation of HCO3\(^{-}\) from CO\(_2\) and H\(_2\)O in the epithelial cells partly contributes toward basal DBS but not toward S3226-stimulated DBS in rats. Because apical perfusion of methazolamide inhibited basal DBS, the other source of HCO3\(^{-}\) for secretion is uptake into the cells via NBC1 (3, 4, 22). However, from our results, DIDS, an anion transport inhibitor, increased rather than decreased basal DBS. Thus we cannot conclude which process is more important for basal DBS. In either case, we showed DIDS did not inhibit S3226-stimulated DBS, suggesting that uptake of HCO3\(^{-}\) via NBC1 is not involved in S3226-stimulated DBS.

Regardless of stimulus, DBS is slowly activated. The mechanism underlying this delayed rise of secretion is unknown. One possibility is that stimulation of DBS requires trafficking of transporter-containing vesicles from a subapical pool to the apical membrane before the initiation of secretion. This content ion is supported by data in which CFTR function appears to be regulated in this fashion (7, 8, 25). We also observed that enhanced HCO3\(^{-}\) secretion associated with S3226 developed slowly and was present even after inhibitor withdrawal, in contrast with the rapid inhibition of DBS observed after methazolamide administration. This delayed effect may also be due to the known cycling of NHE3 between an apical and subapical pool (2, 11, 23). Further insight into the genesis of these delays.

![Figure 8](image-url)  
Fig. 8. Effects of 0.1 and 0.3 mM 5-nitro-2-(3-phenylpropylamino)-benzoic acid (NPPB) on S3226-augmented DBS measured by the CO\(_2\)-sensitive electrode method. NPPB was added to the perfusate, and then 30 min later S3226 was added to the perfusate. Significantly different from *control (P < 0.05) and #S3226 (P < 0.05).

![Figure 9](image-url)  
Fig. 9. Effect of 10 μM S3226 on pHi. The inhibitor had no effect on pHi, over the time course of the experiment.

**DISCUSSION**

We used low (50 μM) and high (3 mM) doses of DMA, which inhibited NHE1 and 2 and NHE1–3, respectively, and found that only 3 mM DMA increased DBS, suggesting inhibition of NHE3 is essential for increased DBS. Furthermore, we could confirm that the selective inhibitors of NHE3, S1611, and S3226, as well as Na\(^+\)-free perfusion, also increased DBS dose dependently by using the CO\(_2\)-sensitive electrode and the pH-stat methods. These results are consistent with our hypothesis that inhibition of only NHE3 activity but not NHE2 activity increased DBS. These results are consistent with data obtained in transgenic mice that indicated that NHE3 is the primary apical cation exchanger of the small intestine (18, 31). Furthermore, measurements made with CO\(_2\)-sensitive electrodes confirmed that inhibition of NHE3 increased true DBS and not an apparent increase of DBS due to decreased NHE3-mediated duodenal acid secretion. With the pH-stat method, CO\(_2\) produced from secreted H\(^+\) combining with secreted HCO3\(^{-}\) is expelled by bubbling with 100% O\(_2\). The pH-stat method thus detects only H\(^+\) loss or HCO3\(^{-}\) increase. Conversely, the CO\(_2\)-sensitive electrode, only measures HCO3\(^{-}\) or CO\(_2\) concentrations, which are not confounded by epithelial H\(^+\) secretion (3, 15).

The mechanism by which inhibition of NHE3 activity increased DBS, especially by S3226, is not well understood. The prostaglandin-cAMP pathway is important for basal and acid-stimulated DBS (16, 41). Indomethacin, generally used as a nonselective cyclooxygenase inhibitor, inhibits basal and acid-induced DBS (41); leukotriene C4/D4 antagonist L-649–923-induced DBS (26); and YM-14673, a thyrotropin-releasing hormone analog induced DBS (40). Nevertheless, because indomethacin did not affect S3226-induced DBS, prostaglan-
NHE3 and HCO$_3^-$ carbonic anhydrase were not involved in this effect. Because intracellular acidification, or intracellular HCO$_3^-$ affects other pathways involved with DBS. Increased DBS. Because the CO$_2$ concentration increased in association with acute inhibition of NHE3 activity, particularly in an is a plausible molecular mechanism underlying the reciprocal cAMP to inhibit NHE3 activity is impaired (1, 13). Thus there is evidence for PDZ binding motif of CFTR and NHE3 are both thought to bind NHE regulatory factor (27). Not only is there evidence for a molecular association between CFTR and NHE3, but also there is a suggestion that CFTR inversely regulates NHE3 activity. The cyclic nucleotide cAMP increases CFTR-mediated Cl$^-$ secretion while inhibiting NHE3-mediated Na$^+$ absorption (45). Stable NHE3 expression downregulates CFTR activity in cultured renal cells (9). In NHE3 null mouse colon, DRA transcripts, which are associated with HCO$_3^-$ activity in cultured renal cells (49). In NHE3 null mouse colon, or in pancreatic-derived PS120 cells transfected with a PDZ-deficient CFTR transcript, the ability of cAMP to inhibit NHE3 activity is impaired (1, 13). Thus there is a plausible molecular mechanism underlying the reciprocal CFTR/anion transporter interaction, although no group before us has demonstrated the upregulation of CFTR function associated with acute inhibition of NHE3 activity, particularly in an in situ preparation. Taken together, inhibition of apical membrane NHE3 activity by S3226, S1611, perfusate Na removal, and DMA increased DBS. Because the CO$_2$ concentration increased in parallel with titratable alkalinity, NHE3 inhibition increased HCO$_3^-$ secretion in addition to decreasing luminal H$^+$ entry. Prostaglandin synthesis, Na$^+$-HCO$_3^-$ cotransporter activation, intracellular acidification, or intracellular HCO$_3^-$ formation by carbonic anhydrase were not involved in this effect. Because NHE3 and HCO$_3^-$ secretion are inversely regulated, we speculate that NHE3 inhibition upregulated CFTR or DRA function via protein-protein or protein-DNA interactions but did not affect other pathways involved with DBS.

ACKNOWLEDGMENTS

The authors thank Dipy Shah and Ritu Jain for technical assistance and Rebecca Cho for artistic and secretarial support.

DISCLOSURES

This study was supported by Veterans Affairs Merit Funds and National Institute of Diabetes and Digestive and Kidney Diseases Grant 2-R01-DK54221.

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