5-Amino-2-hydroxybenzoic Acid 4-[(5-Thioxo-5H-[1,2]dithiol-3yl)-phenyl Ester (ATB-429), a Hydrogen Sulfide-Releasing Derivative of Mesalamine, Exerts Antinociceptive Effects in a Model of Postinflammatory Hypersensitivity

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ABSTRACT

H₂S functions as a neuromodulator and exerts anti-inflammatory activities. Recent data indicate that irritable bowel syndrome (IBS) is linked to inflammation of the gastrointestinal tract. In this study, we have investigated the role of a novel H₂S-releasing derivative of mesalamine (5-amino-2-hydroxybenzoic acid 4-[(5-thioxo-5H-[1,2]dithiol-3yl)-phenyl ester, ATB-429) in modulating nociception to colorectal distension (CRD), a model that mimics some features of IBS, in healthy and postcolitic rats. Four graded (0.4–1.6 ml of water) CRDs were produced in conscious rats, and colorectal sensitivity and pain were assessed by measuring the abdominal withdrawal response and spinal c-Fos expression. In healthy rats, ATB-429 dose dependently (25, 50, or 100 mg/kg) attenuated CRD-induced hypersensitivity and significantly inhibited CRD-induced overexpression of spinal c-Fos mRNA, whereas mesalamine had no effect. ATB-429-induced antinociception was reversed by glibenclamide, a ATP-sensitive K⁺ (Kₐtp) channel inhibitor. The antinociceptive effect of ATB-429 was maintained in a rodent model of postinflammatory hypersensitivity (4 weeks after colitis induction). At a dose of 100 mg/kg, ATB-429 reversed the allodynic response caused by CRD in postcolitic rats. Colonic cyclooxygenase-2 and interleukin-1β mRNA and spinal c-Fos mRNA expression were significantly down-regulated by ATB-429, but not by mesalamine. ATB-429, but not mesalamine, increased blood concentrations of H₂S in both healthy and postcolitic rats. Taken together, these data suggest that ATB-429 inhibits hypersensitivity induced by CRD in both healthy and postcolitic, allodynic rats by a Kₐtp channel-mediated mechanism. This study provides evidence that H₂S-releasing drugs might have beneficial effects in the treatment of painful intestinal disorders.

Irritable bowel syndrome (IBS) is a common disorder involving the gastrointestinal tract usually defined by the coexistence of abdominal pain or discomfort and an alteration in bowel habit that cannot be explained by a structural or biochemical abnormality (Thompson et al., 1999). Although the underlying pathophysiological mechanisms remain obscure, psychosocial disturbances, gastrointestinal dysmotility, and altered visceral perception are currently the most accepted hypothesis.

Animal models have provided evidence that inflammation-driven sensory afferent system activation might be a causative factor for development of altered visceral perception. Support for this view comes from the observation that allo-
dynia and/or hyperalgesia develops in animals after resolution of acute infective (Barbara et al., 1997) or chemically induced (Julia et al., 1995; Distrutti et al., 2006) colitis, and by the finding that maternal deprivation-induced visceral hyperalgesia, a model that involves no direct manipulation of the colon, is associated with increased myeloperoxidase (MPO) activity, a measure of colon inflammation (Coutinho et al., 2002). Likewise, low-grade inflammation is found in the colon of IBS patients and is increasingly regarded as a putative causative factor for symptoms development. Support for this concept comes from the following evidence: first, epidemiological studies have shown that infective gastroenteritis is a risk factor for development of IBS-like symptoms, and this association is now referred to as postinfective IBS (Garcia-Rodriguez and Ruigomez, 1999); and second, histological and ultrastructural studies have shown that an increased number of mast cells and T cells are found in the lamina propria of the ileum and colon of IBS patients in comparison with healthy subjects (Barbara et al., 2006). Moreover, there is evidence that, in these postinflammatory states, immune cells localize in proximity to nerve endings, raising the possibility that mediators released from immune cells might alter enteric nerve function and muscle contractility (Barbara et al., 2004). Together, these observations support the concept that IBS is, at least in some patients, the consequence of the failure of the mucosal immune system to attenuate inflammatory response after the clearance of an infectious agent. Evidence does exist that genetic factors may play a role in maintaining intestinal inflammation in specific subsets of IBS patients (Gwee et al., 1996). Finally, further support for a link between inflammation and altered perception is provided by the observation that patients with chronic inflammatory bowel diseases (IBDs) develop IBS-like symptoms and visceral hyperalgesia during the quiescent phases of their diseases (Isgar et al., 1983; Rao et al., 1987). In these patients, mesalamine (5-amino-2-hydroxybenzoic acid) is widely used to maintain remission, although it has no effect in preventing development of IBS-like symptoms.

Gaseous transmitters are a growing family of regulatory mediators involved in regulation of physiological and pathological functions in mammalian tissues (Wang, 2002; Moore et al., 2003). Although NO is the best characterized member of this family, it is increasingly recognized that CO and H₂S also exert regulatory functions (Wang, 2002; Moore et al., 2003). H₂S regulates key neuronal functions, including the induction of hippocampal long-term potentiation, a synaptic model of learning and memory (Abe and Kimura, 1996), and the release of the corticotrophin-releasing hormone from the hypothalamus (Russo et al., 2000). In addition there is evidence that H₂S may act as a proinflammatory mediator (Bhatia et al., 2005; Li et al., 2005). Although the molecular mechanisms involved in these activities are only partially known, it has been shown that H₂S increases cAMP levels in neuronal and glial cell lines and primary neuron cultures and hyperpolarizes dorsal raphe neurons (Moore et al., 2003), contributes to cardioprotection (Pan et al., 2006), and affects insulin secretion from an insulin-secreting cell line (Yang et al., 2005) by activating ATP-sensitive K⁻/K₄ATP channels.

We have recently shown that cystathionine-β synthase (CBS) and cystathionine-γ lyase (CSE), the two major enzymes involved in H₂S generation, are constitutively expressed in colon and spinal cord and that measurable quantities of H₂S are produced by these tissues. Moreover, H₂S administration inhibits colorectal distension (CRD)-induced pain in healthy and alloidyic rats by acting on the K₄ATP channels (Distrutti et al., 2006). Following these initial results, we have examined the effects of ATB-429, a new chemical entity that combines an H₂S-releasing moiety with mesalamine. Here, we have compared the effects of ATB-429 to those of mesalamine in terms of alleviating CRD-induced hypersensitivity in healthy and postcolitic rats.

Materials and Methods

Structure and Purity of ATB-429. The chemical structure of 5-amino-2-hydroxybenzoic acid 4-(5-thioxo-5H-1,2,3-dithiol-5-yl)phenyl ester (ATB-429) is illustrated in Fig. 1, whereas key synthetic steps are shown in Supplemental Fig. 1. The structure of the ATB-429 was verified spectroscopically by proton ¹H NMR and ¹³C NMR. Spectra were recorded on Varian Mercury Plus 400 instrument (Varian, Torino, Italy). Chemical shifts are referred to Me₄Si as internal standard. Mass spectra of the synthesized products were performed on API 2000 mass spectrometry (Applied Biosystems International, Monza, Italy). Melting point was performed on Buchi B-540 instrument (BUCHI Labortechnik AG, Flawil, Switzerland). Purity of the compound was 98%, as assessed by high-performance liquid chromatography (Varian, Torino, Italy). 5-µM-Hydroxyphenyl-1,2-dithione-3-thione (ADT-0H) (Christen, 1995) was used as H₂S-releasing moiety (Fig. 1A).

Materials. Ascorbic acid, salicylic acid, potassium hydroxide, L-cysteine, N-acetyl-L-cysteine, DL-propargylglycine, trichloroacetic acid, pyridoxal-5'-phosphate, polyethylene glycol, glibenclamide, mesalamine, and phosphate-buffered saline were purchased from Sigma-Aldrich (S. Louis, MO). ADT-0H and ATB-429 were provided by Antibe Therapeutics Inc. (Calgary, Alberta, Canada). Tissue protein extraction reagent T-PER was obtained by Pierce Chemical (Rockford, IL). All of the chemicals were of analytical grade and were used without treatment. Deionized water filtered was used for the buffer preparation. Silver and sulfide ion-selective electrode was from ThermoOrion (Beverly, MA).

Animals. Male Wistar rats (200–250 g; Charles River, Monza, Italy) were housed in plastic cages and maintained under controlled conditions with 12-h light/dark cycles with lights on at 7:00 AM. Tap water and standard laboratory chow were freely available. Food was withheld for 12 h before surgical procedures and CRD recordings. After recovery from surgery, the rats were individually trained by spending 2 to 3 h per day in a Plexiglas cage for 2 to 3 days, which allowed them to adjust to a movement-restricted environment. All experimental procedures described below were approved by our institutional animal research committees and were in accordance with nationally approved guidelines for the treatment of laboratory animals. All experiments were performed in conscious rats and were conducted in a blinded manner in that the observer was not aware of the identity or dose of drugs administered to each animal.

Surgical Procedures. Fasting rats were anesthetized with pentobarbital (60 mg/kg i.p.), and a catheter was inserted into the left jugular vein. The catheter was externalized subcutaneously through the dorsal aspect of the neck and protected with a tube attached to the skin for future access. During procedure, body temperature was kept constant at 36–37°C using a homeothermic blanket. Animals exhibiting motor deficits after the surgical procedure were not used in the experiment. After surgery, rats were housed separately and allowed to recuperate for at least 5 days before CRD testing. Rats were allowed to recover from the surgical procedure for 3 days before subsequent training in the Plexiglas cage.

CRD and Behavioral Testing. The night before experiments the balloons were inflated and left overnight, so that the latex stretched and the balloons became compliant. On the testing day, each rat was sedated with ether inhalation, and a 2-cm-long latex balloon was inflated in the colon and allowed them to adjust to a movement-restricted environment. All experiments were performed in conscious rats and were conducted in a blinded manner in that the observer was not aware of the identity or dose of drugs administered to each animal.
inserted intrarectally 2 cm from the anal verge and fixed at the base of the tail. The balloon was connected via a double barreled cannula to a pressure transducer to continuously monitoring the colorectal pressure by a computer (PowerLab PC, ADInstruments, Milford, MA) and to a syringe for inflation/deflation of the balloon. The rats were then housed in a small Plexiglas cage (20 × 8 × 8 cm) on an elevated platform and allowed to regain consciousness and adapt for 1 h. After recovery from sedation, the rats underwent the CRD procedure, and behavioral response was tested in all groups except control group in which no CRD was performed. CRD of 20 s performed every 5 min was applied in increments of 0.4 ml starting from 0.4 ml and increasing to 1.6 ml of water. Animals underwent a double set of CRD. Ten minutes after the first CRD (0.4–1.6 ml of water), drugs were administered i.p. and/or intravenously (i.v.). Five minutes after the end of the drug administration, a second CRD was performed. Behavioral responses and colonic parameters collected during the first and the second sets of CRD were assessed and compared.

The behavioral response to CRD was assessed by measuring the abdominal withdrawal reflex (AWR) using a semiquantitative scoring system (Al-Chaer et al., 2000). The AWR is an involuntary motor reflex similar to the visceromotor reflex, but it has the great advantage that the latter requires abdominal surgery to implant recording electrodes and wires in the abdominal muscle wall, which may cause additional sensitization (Ness and Gebhart, 1990). Measurement of the AWR consisted of visual observation of the rat’s response to graded CRD by a blinded observer and assignment of an AWR score according with the behavioral scale described previously (Al-Chaer et al., 2000) in which grade 0 corresponds to no behavioral response to CRD, grade 1 corresponds to brief head movement at the onset of the stimulus followed by immobility, grade 2 corresponds to a mild contraction of abdominal muscles although the rat does not lift the abdomen off the platform, grade 3 corresponds to a strong contraction of the abdominal muscles with the lifting of the abdomen off the platform, and grade 4 corresponds to a severe contraction of the abdominal muscles manifested by body arching and the lifting of the abdomen and of the pelvic structures and scrotum. The rats that did not show any behavioral response (i.e., score 0) were excluded from further study (approximately 20%). To determine the effect of H$_2$S on colonic smooth muscle, the compliance of the colon during CRD was obtained from colorectal volume and pressure and expressed as milliliters per mm H$_2$O.

Effects of ATB-429 on Colonic Hypersensitivity in Healthy Rats. The control group (n = 5) consisted of fasting rats that underwent the surgical procedures but not CRD, whereas the CRD group consisted of fasting, healthy animals that underwent surgical procedures and two sets of CRD. To investigate whether ATB-429 modulates sensitivity and pain induced by CRD, rats were treated i.p. with ATB-429 at doses of 25, 50, or 100 mg/kg (ATB-429 group), mesalamine at the dose of 100 mg/kg (mesalamine group), or vehicle (CRD group).

The involvement of K$_{ATP}$ channels in the modulation of visceral perception by H$_2$S was assessed by pretreating rats with glibenclamide (K$_{ATP}$ channel blocker) at a dose of 2.8 μmol/kg i.v. for 20 min before ATB-429 administration (glibenclamide plus ATB-429 group) or glibenclamide alone (glibenclamide group). At the end of the CRD procedures, rats were sacrificed and blood, colon, and spinal cord (L1–L5) were collected for further analysis.

Induction of Colitis. Colitis was induced as described previously (Wallace et al., 1989). In brief, rats were anesthetized with 60 mg/kg i.p. pentobarbital. Trinitrobenzene sulfonic acid (TNBS) at a dose of 20 mg/ml in 0.5 ml of 50% ethanol was administered into the distal colon by cannula. The rats were monitored daily for loss of body weight and survival. After 4 weeks, rats still alive were used for a CRD study, as described above. Five rats were immediately sacrificed and served as controls (TNBS group). In the other rats, we performed two consecutive series of CRD without administering drugs (TNBS plus CRD and mesalamine group; n = 5). At the end of the CRD procedures, rats were sacrificed and blood, colon, and spinal cord were collected for further analysis.

Assessment of Colonic Inflammation. Colons were examined blindly with a dissecting microscope (5-fold magnification) and graded for macroscopic lesions on a scale from 0 to 10 based on criteria for inflammation, such as hyperemia, thickening of the bowel and the extent of ulceration (Wallace et al., 1989). Colonic tissue was taken for measurement of MPO activity, an index of granulocyte infiltration, as described previously (Santucci et al., 1995).
In Vitro H$_2$S Release. To compare the in vitro H$_2$S release induced by mesalamine, ATB-429, and ADT-OH, the H$_2$S-releasing moiety of ATB-429, 100 to 150 mg of isolated livers was homogenized in 1 ml of ice-cold T-PER protein extractor. The H$_2$S release was lead on the same reactor of plasma analysis. Two mililiters of an assay reaction mixture was introduced in the reactor. The mixture contained 10 mM ATB-429 or 10 mM ADT-OH dissolved in polyethylene glycol and 100 mM potassium phosphate buffer, pH 7.4. Incubations were lead with or without presence of 10% (v/v) liver homogenate and 2 mM pyridoxal 5'-phosphate. A constant stream of nitrogen was passed through the reactor by gas inlet capillary. Reactions were initiated by transferring the tube from ice bath to a 37°C water bath. The stream of nitrogen carried the sulfide acid into the second reactor containing 2 ml of sulfide antioxidant buffer (SAOB) as described previously. After incubating at 37°C for 90 min, 1 ml of the SAOB solution was removed, and the sulfide concentration was measured with a sulfide-sensitive electrode as described previously (Khan et al., 1980; Ubuka, 2002).

Measurement of Plasma H$_2$S Concentrations. To determine the kinetics of H$_2$S released from ATB-429, groups of four to five rats were treated with ATB-429 at the dose of 100 mg/kg i.p. and sacrificed after 10, 30, 60, and 180 min. A time-course plan of sulfide H$_2$S concentrations was then constructed. Plasma H$_2$S concentrations were measured as described previously (Zhao et al., 2001; Ubuka, 2002) with modifications. In brief, 250 μl of plasma was added to ice-cold 250 μl of 0.1 N NaOH in a sealed three-neck reactor. A constant stream of nitrogen was passed through the mixture via a gas inlet capillary. The reactor was maintained at 37°C, and H$_2$S extraction was started by introducing 1 ml of 10% trichloroacetic acid solution. The stream of nitrogen carried the sulfide acid in another reactor by cooled connector and bubbling in 2 ml of SAOB solution, consisting of 2 M KOH, 1 M salicylic acid, and 0.22 M ascorbic acid at pH 12.8. After 30 min, the SAOB solution was removed, and the sulfide concentration was measured with a sulfide-sensitive electrode (model 9616 S2/B, Thermo Orion) and expressed as H$_2$S (Khan et al., 1980; Ubuka, 2002).

Reverse Transcription-Polymerase Chain Reaction on Colonic and Spinal Tissues. Whether acute administration of ATB-429 could modulate the expression of genes that participate in the control of inflammation and pain was studied by determining the colonic and spinal cord expression of mRNA of CBS, CSE, c-Fos, cyclooxygenase (COX)-1 and -2, tumor necrosis factor (TNF)-α, interleukin (IL)-1β, constitutive NO synthase (cNOS), calcitonin gene-related peptide (CGRP), and takikinin (TAC)-1 and -2 in postcolitic rats. In brief, total RNA was isolated from rat colon and spinal cord homogenates, suggesting that this compound effectively generates H$_2$S both by nonenzymatic and enzymatic activities, although the nature of the enzymes involved in this process was not addressed. The amount of H$_2$S released in vitro by ATB-429 was significantly higher than that released by ADT-OH alone.

To investigate whether ATB-429 releases H$_2$S in vivo, plasma H$_2$S concentrations were measured in rats administered 100 mg/kg ATB-429 i.p. (Fig. 1C). ATB-429 increased plasma H$_2$S concentrations in a time-dependent manner with a peak occurring 10 min after drug injection (n = 4–5; * P < 0.05 versus basal), and concentrations returned to basal values 60 min later. Due to this kinetics, all of the distension experiments described hereafter were carried out 10 to 30 min after ATB-429 administration.

ATB-429 Does Not Induce Colonic Damage. Macroscopic examination of the colon revealed that the inflammation scores after CRD alone or CRD plus drug administration were similar to those of control group (data not shown). Moreover, MPO activity in colonic tissue during CRD was similar to that of the control group, indicating that CRD did not produce a significant colonic inflammatory response. Administration of mesalamine, ATB-429, or glibenclamide did not significantly affect colonic MPO activity (data not shown).

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<th>Antisense Primer (5′-3′)</th>
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<tr>
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**TABLE 1** Rat primers (sense and antisense) used in this study. Specific primers (30 μM). Primer concentrations in the final volume of 25 μ1 were 300 nM. All reactions were performed in triplicate in an iCycler iQ system (Bio-Rad, Hercules, CA), and thermal cycling conditions were 15 min at 95°C, followed by 40 cycles of 9°C for 10 s, 55°C for 10 s, and 72°C for 20 s. Statistical Analysis. All data are presented as the mean ± S.E.M., with sample sizes of at least five rats per group. In the RT-PCR experiments, the ratio between each gene product and glyceraldehyde-3-phosphate dehydrogenase in control animals was considered as 1. Statistical comparisons of unpaired data were performed by the Mann–Whitney U-test, whereas statistical comparisons of paired data were performed by the Wilcoxon signed rank test. An associated probability (P value) of less than 5% was considered significant.
ATB-429 Inhibits CRD-Induced Hypersensitivity in Healthy Rats. In all experiments, two sequential distension-effect curves were constructed. The first distension-effect curve acted as basal, and the second curve was constructed following vehicle or drug administration. In all experiments, rats were conscious, and none of the treatments induced changes in the state of consciousness. CRD elicited volume-dependent increases in the AWR score, which were rapid in onset and persisted for the duration of the distension period (Fig. 2A) with no significant reduction in colorectal pressure (Fig. 2B). Distensions with 0.4 ml of water induced a slight increase of the AWR score (less than 1) that was associated with a small rise of colorectal pressure (~20 mm Hg), indicating that this CRD represents a nonpainful stimulus. Distensions with 1.2 and 1.6 ml of water were associated with greater AWR scores (3 and 4, respectively) and with a high colorectal pressures (up to 80 mm Hg), indicating that these volumes induced noxious sensations (Ji and Traub, 2001). Mesalamine (100 mg/kg i.p.) caused only a slight reduction of the AWR score, reaching statistical significance only at the greatest volume (1.6 ml) (Fig. 2C). It did not affect the colorectal compliance (Fig. 2D).

In contrast, ATB-429 (100 mg/kg i.p.) caused a significant decrease of the AWR response to CRD (Fig. 2E) with a con-
comitant increase in rectal compliance (Fig. 2F). The antinociceptive effects of ATB-429 during CRD were confirmed by analysis of c-Fos expression in the spinal cord. Quantitative RT-PCR of c-Fos mRNA expression demonstrates that CRD induced a 2-fold increase in spinal c-Fos expression that was not modified by mesalamine. Administration with ATB-429 abrogated c-Fos mRNA induction caused by CRD, suggesting that the reduced AWR score was due to the antinociceptive effect of the H$_2$S moiety of ATB-429, rather than the mesalamine component of the new molecule (Fig. 2G).

The antinociceptive effect of ATB-429 was dose-dependent, because it was maximal at the dose of 100 mg/kg (Fig. 3A), it was maintained at the dose of 50 mg/kg (Fig. 3C), but it was not apparent at the dose of 25 mg/kg (Fig. 3E). The relaxant effect was demonstrated only at the highest dose (Fig. 3, B, D, and F).

**K$_{ATP}$ Channel Blockade Reverses the Antinociceptive Effect of ATB-429.** To determine whether ATP-sensitive K$^+$ channels were involved in the antinociceptive effects of ATB-429, the interaction of ATB-429 with a known K$_{ATP}$ channel modulator was examined. The inhibitory effect of ATB-429 on CRD-induced pain was reversed by pretreating rats with glibenclamide, a K$_{ATP}$ channel antagonist (Fig. 4A), and this effect was accompanied by inhibition of colonic smooth muscle relaxation (Fig. 4B). In contrast, treating rats with glibenclamide alone had no effect on CRD-induced nociception or colonic compliance (data not shown). Analysis of c-Fos expression demonstrated that pretreatment with glibenclamide reversed the antinociceptive effect of ATB-429 (Fig. 4C). Plasma H$_2$S concentrations did not significantly change during K$_{ATP}$ channel modulator pretreatment (data not shown).
ATB-429 Inhibits Pain in Allodynic Rats. Colitic rats exhibited a 20% reduction of body weight compared with healthy rats, and diarrhea was observed during the first week after induction of colitis. Four weeks after induction of colitis, colonic MPO activity was not significantly increased in TNBS-treated rats in comparison with controls (Fig. 5A), indicating that inflammation was almost resolved. These data were confirmed by the analysis of the macroscopic inflammatory score that demonstrated that only thickening of bowel wall was observed in TNBS-treated rats compared with controls, whereas hyperemia and ulceration had disappeared (Fig. 5B).

When CRD was performed 4 weeks after induction of colitis, a significant increase in the AWR score was observed in comparison with healthy rats. As shown in Fig. 6A, an increased nociception was observed during the low-volume (0.4 and 0.8 ml of water) and high-volume (1.2 ml of water) distensions, indicating that colonic inflammation induces allodynia (perception of nonpainful stimulus as painful) and hyperalgesia (perception of painful stimulus as more painful) to CRD. Interestingly, colonic compliance of postcolitic rats was also significantly lower than that of control animals (Fig. 6B), probably due to the fibrotic evolution of the colitis. The AWR score and colonic compliance in response to repeated CRDs and CRD + mesalamine (100 mg/kg i.p.) did not change (Fig. 6, C and D, respectively), whereas pretreating colitic rats with 100 mg/kg i.p. ATB-429 almost completely inhibited the allodynic response to CRD (Fig. 6E) without modifying the colonic compliance (Fig. 6F). The expression of c-Fos mRNA in the spinal cord was greatly increased in the colitic rats after CRD, indicating the presence of a painful condition after induction of colitis. The administration of ATB-429, but not of mesalamine, reduced c-Fos mRNA expression to values similar to that of controls (Fig. 6G).

Plasma Concentration of H$_2$S. In experiments with both healthy (Fig. 7A) and postcolitic (Fig. 7B) rats, plasma concentrations of H$_2$S significantly increased after ATB-429 administration. In contrast, repeated CRD or mesalamine administration had no effect.

Colonic and Spinal Cord Gene Expression. TNBS-induced colonic inflammation resulted in up-regulation of CBS and CSE mRNAs, which was not modified by ATB-429 administration, whereas mesalamine down-regulated CBS expression (Fig. 8). Moreover, in postcolitic rats, we observed an overexpression of COX-1, COX-2, TNF$\alpha$, IL-1$\beta$, and nNOS mRNAs that was not modified by CRD or mesalamine administration (Fig. 9), whereas ATB-429 significantly inhibited the colonic expression of COX-2 and IL-1$\beta$ (Fig. 9, B and D, respectively). TNBS-induced colitis was associated with increased CGRP, TAC-1, and TAC-2 mRNA expression in the colon that was not modified by mesalamine or ATB-429 administration (data not shown).
TNBS-induced colonic inflammation did not modify spinal cord expression of CBS and elicited only a slight increase in CSE expression (data not shown); CRD and administration of either mesalamine or ATB-429 had no effect on expression of these genes (data not shown). Likewise, in TNBS groups, we did not observe any significant modification of inflammatory gene expression except IL-1β that was reduced by ATB-429, but not mesalamine (data not shown). CRD induced a significant overexpression of spinal COX-2 and TNF-α that was only partially reversed by mesalamine and ATB-429 (data not shown). Finally, we did not observe any significant modification of spinal CGRP, TAC-1, or TAC-2 mRNA expression after induction of colitis, and CRD, mesalamine, and ATB-429 did not modify expression of these genes (data not shown).

Discussion

The studies described herein demonstrate that ATB-429, an H₂S-releasing derivative of mesalamine, functions as an antinociceptor in healthy rats and in a postcolitic model of
rectal hypersensitivity. These effects are produced, at least in part, through K<sub>ATP</sub> channels. ATB-429 is a new chemical entity consisting of an H<sub>2</sub>S-releasing moiety (a thione group) linked to mesalamine, a known anti-inflammatory agent, and, it is noteworthy that a 100-mg/kg dose of ATB-429 delivers only 38 mg/kg mesalamine. Here, we provide evidence that ATB-429 is significantly more effective than mesalamine in controlling pain in the model. Second, ATB-429, but not mesalamine, releases H<sub>2</sub>S in vitro, and it does the same in vivo, with a peak of plasma H<sub>2</sub>S concentration occurring rapidly (10–30 min) after i.p. administration (100 mg/kg). Third, two pharmacological actions of ATB-429, antinociception and reduction of c-Fos expression in the spinal cord, were reversed by glibenclamide, a K<sub>ATP</sub> channel inhibitor (Edwards and Weston, 1993; Distrutti et al., 2006). Several H<sub>2</sub>S activities have been shown to be mediated via K<sub>ATP</sub> channels (Wang, 2002), and this finding is consistent with our previous observation demonstrating that antinociception exerted by H<sub>2</sub>S is glibenclamide-sensitive (Distrutti et al., 2006). K<sub>ATP</sub> channels are expressed in many excitable cells, including skeletal and smooth muscle cells as well as neurons from both central and peripheral nervous system. Because these receptors are not discriminated by glibenclamide, the use of this agent does not allow for identification of the site of action of ATB-429 (central versus peripheral) and deserves further investigation.

The antinociceptive action of ATB-429 is maintained in a rodent model of postinflammatory pain. In animal models of acute (Bonaz et al., 2000) and chronic (Julia et al., 1995)
inflammation, abnormal pain responses to CRD have been observed, demonstrating that inflammation induces both hyperalgesia and allodynia that persist when local inflammation is partially or totally resolved. Human studies in patients with ulcerative colitis and Crohn’s disease (Bernstein et al., 1996; Chang et al., 2000) and IBS (Collins et al., 2001) have confirmed that colonic inflammation modulates colonic neural afferents. In the present study, an elevated AWR score was observed in postcolitic rats in response to low-volume distension (0.4 and 0.8 ml of water), confirming that TNBS-induced inflammation causes allodynia. Moreover, c-Fos mRNA expression was increased in postcolitic rats in comparison with healthy controls, suggesting that colonic inflammation activates a population of second order spinal cord neurons (Traub et al., 1992). Of interest, ATB-429 completely reversed the allodynic effect of colonic inflammation and down-regulated c-Fos mRNA expression in the spinal cord.

Several inflammatory and noninflammatory mediators are thought to be involved in the hyperalgesia and/or allodynia observed in postinflammatory states. Here, we found that colonic expression of COX-1, COX-2, TNF-α, IL-1β, cNOS, CGRP, TAC-1, and TAC-2 increased in postcolitic rats in comparison with healthy rats. Previous studies have associated the increased expression of these mediators with development of hypersensitivity, and their mechanistic role has been investigated by pharmacological and genetic approaches (Abbadie, 2005). The development of hypersensitivity in postinflammatory states supports the notion that inflammation induces long-lasting changes in the mechanisms underlying visceral pain. Structural and molecular changes take place in the colon of IBS patients and along with the demonstration that IBS-like symptoms develop in postinfectious colitis, these data support the notion that intestinal inflammation plays a crucial role in precipitating IBS symptoms in susceptible individuals (Sartor, 1994). Further supporting the link between inflammation and IBS, IL-1β has been found to be elevated in the colonic mucosa of a subset of diarrhea-predominant IBS patients (Sartor, 1994), and COX-2 is up-regulated in animal model in which transient acute infection leads to persistent muscle hypercontractility (Akiho et al., 2005). Moreover, it has been demonstrated that IL-1β induces spinal COX-2 up-regulation and pain hypersensitivity following peripheral inflammation (Lee et al., 2004). In the present study, we have shown that colon expression of IL-1β and COX-2 mRNA was persistently increased after TNBS-induced inflammation and that ATB-429, but not mesalamine, reduced the colonic expression of these mediators. Previous studies have shown that H₂S exerts anti-inflammatory activities and, similar to NO, reduces neutrophil adherence to endothelial cells in the mesenteric circulation (Fiorucci et al., 2005), suggesting that the H₂S-


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