Enhanced Analgesic Effects and Gastrointestinal Safety of a Novel, Hydrogen Sulfide-Releasing Anti-Inflammatory Drug (ATB-352): A Role for Endogenous Cannabinoids

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Abstract

Aims: The covalent linking of nonsteroidal anti-inflammatory drugs to a hydrogen sulfide (H2S)-releasing moiety has been shown to dramatically reduce gastrointestinal (GI) damage and bleeding, as well as increase anti-inflammatory and analgesic potency. We have tested the hypothesis that an H2S-releasing derivative of ketoprofen (ATB-352) would exhibit enhanced efficacy without significant GI damage in a mouse model of allodynia/hyperalgesia.

Results: ATB-352 was significantly more potent and effective as an analgesic than ketoprofen and did not elicit GI damage. Pretreatment with an antagonist of the CB1 cannabinoid receptor (AM251) significantly reduced the analgesic effects of ATB-352. The CB1 antagonist exacerbated GI damage when coadministered with ketoprofen, but GI damage was not induced by the combination of ATB-352 and the CB1 antagonist.

In vitro, ATB-352 was substantially more potent than ketoprofen as an inhibitor of fatty acid amide hydrolase, consistent with a contribution of endogenous cannabinoids to the analgesic effects of this drug. Blood anandamide levels were significantly depressed by ketoprofen, but remained unchanged after treatment with ATB-352.

Innovation: Ketoprofen is a potent analgesic, but its clinical use, even in the short term, is significantly limited by its propensity to cause significant ulceration and bleeding in the GI tract. Covalently linking an H2S-releasing moiety to ketoprofen profoundly reduces the GI toxicity of the drug, while boosting analgesic effectiveness.

Conclusion: This study demonstrates a marked enhancement of the potency and effectiveness of ATB-352, an H2S-releasing derivative of ketoprofen, in part, through the involvement of the endogenous cannabinoid system. This may have significant advantages for the control and management of pain, such as in a postoperative setting.

Keywords: inflammation, pain, hydrogen sulfide, ulcer, analgesic, ketoprofen, cannabinoid

Introduction

Postoperative pain relief facilitates recovery from injury (12, 15), but optimal perioperative or postoperative treatments remain problematic. While opioids are very effective analgesics, the significant risk of addiction is a major barrier to their use, even in the short term. Nonsteroidal anti-inflammatory drugs (NSAIDs) can be effective in managing pain, but their use is limited by the substantial risk of bleeding, particularly in the gastrointestinal (GI) tract (24). While proton pump inhibitors and histamine H2-receptor antagonists can reduce such bleeding in the stomach and...
proximal duodenum, they offer no benefit in the remainder of the GI tract, where significant NSAID-induced ulceration and bleeding can occur (25a). Indeed, suppressors of acid secretion can significantly exacerbate ulceration and bleeding in the intestine (17, 30, 35, 36).

In animal models, derivatives of NSAIDs that contain a hydrogen sulfide (H₂S)-releasing moiety have been shown to produce markedly lower levels of GI damage and bleeding than the parent NSAIDs (8, 27). These H₂S-NSAIDs produce more potent suppression of prostaglandin synthesis (cyclooxygenase activity; COX) than that observed with the parent NSAID, particularly in humans (26). A marked increase in GI safety of an H₂S-releasing NSAID was recently demonstrated in humans (29). Rates of upper GI ulceration were examined endoscopically in a double-blind, phase 2 clinical trial involving 244 subjects taking equieffective doses of either naproxen or ATB-346 for two weeks (29). The rate of ulceration in the subjects taking naproxen was 42.2%, while that in subjects taking ATB-346 was dramatically reduced (to 2.5%; \( p < 0.001 \)).

In the present study, we evaluated the analgesic efficacy of an H₂S-releasing derivative of ketoprofen (ATB-352) versus equimolar doses of ketoprofen in a mouse model of enhanced sensitivity to pain (mechanical allodynia/hyperalgesia). Ketoprofen is a very potent NSAID, but is among the most GI toxic of this class of drugs (7, 34). ATB-352 has been shown to be GI safe in animal models despite profound suppression of COX activity (8) and it does not activate mu opioid receptors at concentrations up to 30 \( \mu \)g/mL. We also examined the potential contribution of the endogenous cannabinoid, anandamide, to the analgesic potency and GI safety of ATB-352.

**Results**

ATB-352 exhibits enhanced analgesic potency versus ketoprofen

In vehicle-treated mice, there was a rapid and marked increase in mechanical allodynia 24 h after the incision had been made (Fig. 1). This remained unchanged throughout the 5-h postincision observation period (Fig. 1A–C). The mechanical allodynia responses were not affected by the lowest or intermediate doses of ketoprofen (3 and 10 mg/kg), but treatment with equimolar doses of ATB-352 (4.6 and 15 mg/kg) significantly attenuated postoperative pain from 1 to 3 h postdose (Fig. 1A, B). A higher dose of ketoprofen (30 mg/kg; p.o.) was required to significantly reduce pain sensitivity (Fig. 1C), and at an equimolar dose (46 mg/kg), ATB-352 markedly reduced the pain response in mice 0.5, 1, 2, and 3 h after treatment (Fig. 1C).

**Role of CB1 in pain response and GI injury**

Anandamide, an endogenous cannabinoid, has been implicated as an analgesic mediator through activation of CB1 receptors as well as contributing to NSAID-related analgesia (22). The analgesic effects of ketoprofen at 30 mg/kg were comparable with those of one-third the molar equivalent dose of ATB-352. Pretreatment with the CB1 antagonist, AM251 (22), reversed the analgesic effect of ATB-352, but did not reduce the analgesic effect of ketoprofen (Fig. 2).
suggests that a significant component of the analgesic effects of ATB-352 is attributable to endogenous cannabinoids. Anandamide can also increase the resistance of the GI mucosa to injury, as demonstrated in several animal models (8, 21, 22). We have previously reported that antagonism of CB1, but not CB2, receptors reversed the protective effects of a cannabis extract against naproxen-induced GI damage (28). Moreover, activation of CB1 (but not CB2) has been shown to enhance colitis-associated pain in rats (20). In the present study, pretreatment with the selective CB1 receptor antagonist, AM251, resulted in an approximately threefold increase ($p < 0.05$) in the extent of gastric damage in mice treated with 30 mg/kg ketoprofen, while in mice treated with an equimolar dose of ATB-352 the CB1 antagonist did not affect the extent of mechanical allodynia. In contrast, the mechanical allodynia observed in mice treated with equimolar doses of ATB-352 was significantly reduced by pretreatment with the CB1 antagonist ($p < 0.05$). Data were analyzed by one-way ANOVA, followed by the Bonferroni multiple comparison test, and data are presented as the mean ± SEM ($n=6$ per group).

In vitro inhibition of fatty acid amide hydrolase

COX-2 inhibitors can inhibit fatty acid amide hydrolase (FAAH), thereby reducing catabolism of anandamide and contributing to analgesia and GI protection (13). We
IC50 values of 340 nM and 0.02 and <2.52, respectively, corresponding to mean IC50 values of 340 nM and >300 mM. Data are shown as the means (n = 3 per group). FAAH, fatty acid amide hydrolase; H2S, hydrogen sulfide.

The marked increase in FAAH inhibitory potency of ATB-352 over that of ketoprofen was confirmed in an "in vitro" assay (unpublished data), this drug may represent an attractive alternative to opioids for severe pain relief and therefore a potential solution to at least part of the opioid crisis. In the present study, it exhibited a significant increase in potency of pain relief in a well-characterized surgical incision model (19) compared with ketoprofen (steady-state plasma ketoprofen levels in the ATB-352-treated animals were ~3–5 μM). Moreover, in contrast to generation of hemorrhagic GI lesions in mice treated with ketoprofen, such damage was not observed in the mice treated with ATB-352.

In recent years, substantial evidence has been generated for a significant interplay between arachidonic acid metabolism and endogenous cannabinoids. FAAH catalyzes the hydrolysis of anandamide and other similar lipid amides (22). COX-2 inhibitors can reduce this hydrolysis, leading to increased levels of endogenous cannabinoids (including anandamide) and thereby enhancing analgesia. In contrast, treatment with a CB1 antagonist can inhibit the actions of endogenous cannabinoids, thereby reducing analgesia. Thus, in the present study, oral administration of a selective CB1 antagonist (AM251) profoundly reduced the analgesic effects of ATB-352, while not affecting Those of ketoprofen. On the other hand, increased FAAH-catalyzed hydrolysis of endogenous cannabinoids can reduce analgesia and increase susceptibility to GI ulceration (9, 21, 22, 28). This was confirmed in the present study by the observation that treatment with the selective CB1 antagonist resulted in a profound increase in hemorrhagic damage in the GI tract of the ketoprofen-treated mice (5-to 10-fold vs. the ATB-352-treated mice). The lack of damage in the ATB-352-treated mice following administration of the CB1 antagonist strongly suggests the existence of additional protective mechanisms, likely related to H2S (Fig. 6). Plasma anandamide levels decreased significantly in the ketoprofen-treated mice, measured 5h after drug administration, which was consistent with the observed increase in susceptibility to GI injury. In contrast, anandamide levels remained unchanged in the mice treated with ATB-352. These observations are consistent with the study by Goodman et al. (10), who reported that NSAIDs that inhibit both COX and FAAH exhibit decreased GI damage, possibly as a result of increased levels of fatty acid ethanolamides.

The marked increase in FAAH inhibitory potency of ATB-352 over that of ketoprofen was confirmed in an "in vitro study with a goal of gaining a better understanding of the mechanisms underlying the increased potency and GI safety of ATB-352 versus ketoprofen. Since ATB-352 does not activate mu opiate receptors at concentrations up to 30 μM (unpublished data), this drug may represent an attractive alternative to opioids for severe pain relief and therefore a potential solution to at least part of the opioid crisis. In the present study, it exhibited a significant increase in potency of pain relief in a well-characterized surgical incision model (19) compared with ketoprofen (steady-state plasma ketoprofen levels in the ATB-352-treated animals were ~3–5 μM). Moreover, in contrast to generation of hemorrhagic GI lesions in mice treated with ketoprofen, such damage was not observed in the mice treated with ATB-352.

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H₂S-releasing NSAIDs have consistently exhibited substantially enhanced potency versus the parent drug. H₂S-releasing NSAIDs (and H₂S donors) markedly reduce the severity of NSAID-induced gastrointestinal damage while also promoting resolution of inflammation and repair of tissue damage. H₂S-releasing NSAIDs also exhibit markedly enhanced potency with respect to inhibition of FAAH, resulting in maintained or enhanced levels of endogenous cannabinoids, such as anandamide. As shown in this study, endogenous cannabinoids contribute significantly to the enhanced analgesic effects of ATB-352, as well as to the markedly improved gastrointestinal safety versus a conventional NSAID (ketoprofen). NSAID, nonsteroidal anti-inflammatory drugs.

FIG. 6. The analgesic effects of ATB-352 include contributions from H₂S, cyclooxygenase inhibition, and endogenous cannabinoids. H₂S-releasing NSAIDs have been shown to be more potent than the parent drug. H₂S-releasing NSAIDs (and H₂S donors) markedly reduce the severity of NSAID-induced gastrointestinal damage while also promoting resolution of inflammation and repair of tissue damage. H₂S-releasing NSAIDs also exhibit markedly enhanced potency with respect to inhibition of FAAH, resulting in maintained or enhanced levels of endogenous cannabinoids, as anandamide. As shown in this study, endogenous cannabinoids contribute significantly to the enhanced analgesic effects of ATB-352, as well as to the markedly improved gastrointestinal safety versus a conventional NSAID (ketoprofen). NSAID, nonsteroidal anti-inflammatory drugs.

Materials and Methods

In vivo studies

Adult, male BALB/c mice (20–30 g; 7–8 week old), obtained from the animal rearing facilities at the Faculty of Medicine, University of São Paulo, Brazil, were used in the experiments in accordance with the Ethical Principles for Animal Research established by the ICB/USP Ethics Committees for Animal Use in Research, according to the National Council for Animal Experimentation Control principles, consistent with the Animal Welfare Act. According to the internal laboratory rules, euthanasia was to be performed if severe distress related to the protocol developed during the experiment. The mice were group-housed in a temperature-controlled room at 22°C with a 12-h light/12-h dark cycle and allowed free access to food (Nuvilab CR-1; Quintia S/A, Brazil) and filtered water.

ATB-352 was provided by Antibe Therapeutics, Inc., while ketoprofen was purchased from Sigma-Aldrich (Oakville, ON, Canada). Suspensions were prepared in 0.5% carboxymethylcellulose (CMC; Cromoline Química Fina Ltd., Diadema, SP, Brazil) with the aid of a vortex mixer.

The mice were orally treated with vehicle (4 mL/kg of 0.5% CMC), ketoprofen (3, 10, or 30 mg/kg), or equimolar doses of ATB-352 (4.6, 15, or 46 mg/kg). The ability of ATB-352 and equimolar doses of ketoprofen to reduce postoperative pain was examined using a plantar incision model, as described by Brennan et al. (2), and modified for use in mice by Pogatzki and Raja (19). The mice were anesthetized with inhaled 1.5%–2% isoflurane (v/v in O₂), delivered via a plastic nose cone, followed by antisepsic (10% povidone–iodine solution) preparation of the right hind paw. Subsequently, a 5-mm longitudinal incision was made with a number 11 surgical blade, starting 2 mm from the proximal edge of the heel and extending toward the toes, through the plantar foot skin and fascia. With the aid of a curved forceps, the underlying muscle and tendons were carefully elevated, then replaced to the normal anatomical position. After controlling bleeding, the skin was sutured with 6–0 nylon in the middle of the incision. The wound was coated with 10% povidone–iodine solution and mice were allowed to recover in their cages until the following day. Control (sham-treated) mice underwent anesthesia and antisepsic procedures, without an incision. At the end of the experiments, all mice were euthanized with an overdose of isoflurane, followed by cervical dislocation.

Measurement of mechanical paw withdrawal threshold was assessed blindly using von Frey filament stimulation to reduce postoperative pain was examined using a plantar incision model, as described by Brennan et al. (2), and modified for use in mice by Pogatzki and Raja (19). The mice were anesthetized with inhaled 1.5%–2% isoflurane (v/v in O₂), delivered via a plastic nose cone, followed by antisepsic (10% povidone–iodine solution) preparation of the right hind paw. Subsequently, a 5-mm longitudinal incision was made with a number 11 surgical blade, starting 2 mm from the proximal edge of the heel and extending toward the toes, through the plantar foot skin and fascia. With the aid of a curved forceps, the underlying muscle and tendons were carefully elevated, then replaced to the normal anatomical position. After controlling bleeding, the skin was sutured with 6–0 nylon in the middle of the incision. The wound was coated with 10% povidone–iodine solution and mice were allowed to recover in their cages until the following day. Control (sham-treated) mice underwent anesthesia and antisepsic procedures, without an incision. At the end of the experiments, all mice were euthanized with an overdose of isoflurane, followed by cervical dislocation.

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(0.04–4 g; North Coast Medical, Inc., Morgan Hill, CA) perpendicularly to the ventral surface of the right hind paw to determine the 50% threshold (g) based on the up and down paradigm (5). Groups of 6 mice each were randomly assigned to be treated orally with vehicle (0.5% carboxymethylcellulose, 4 mL/kg), ketoprofen (3, 10, or 30 mg/kg), or equimolar doses of ATB-352 (4.6, 15, or 46 mg/kg). The mice were then placed individually into a transparent plastic box (18 x 11 x 20 cm; Insight, Inc., Ribeirão Preto, SP, Brazil) on an elevated mesh platform and allowed to acclimatize for 1–2 h before testing. In a blinded manner, von Frey filaments ranging from 0.4 to 4.0 g were applied to the plantar surface of the right hind paw (avoiding the toes, heel, and pads) for 1–2 s with an interstimulus interval of at least 5 s. The mechanical allodynia (g) was evaluated immediately before the incision (basal response), at 24 h after surgery (time 0), and at 0.5, 1, 2, 3, 4, and 5 h thereafter. At the end of the experiments, all mice were euthanized with an overdose of isoflurane, followed by cervical dislocation.

**Plasma anandamide levels and effects of CB1 antagonist**

After completion of the assessment of pain, blood was drawn from mice for measurement of plasma anandamide levels (*i.e.* 5 h after drug/vehicle administration; ketoprofen at 10 mg/kg and ATB-352 at 15 mg/kg). The mice were anesthetized with inhaled 2% isoflurane (v/v in O2) to facilitate blood collection using a heparinized syringe. Plasma was obtained from blood samples by centrifugation (2000 g at 4°C for 10 min) and then frozen on dry ice and stored at −80°C. Plasma aliquots (50 μL) were diluted (1:2) in phosphate-buffered saline (pH 7.4) and centrifuged (10,000 g at 4°C for 15 min). The anandamide levels were quantified using a competitive inhibition enzyme-linked immunosorbent assay, according to the manufacturer’s instructions (Biomatik Corporation, Cambridge, ON, Canada). The results were interpolated with an anandamide standard curve and expressed as ng/mL of plasma.

The potential roles of CB1 in the analgesic and GI-damaging effects of ketoprofen and ATB-352 were also examined. Groups of mice (n=6) were orally administered vehicle (phosphate-buffered saline) or the CB1 antagonist, AM251 (3 mg/kg i.p.) (22), and 30 min later, they were orally treated with ketoprofen (10 or 30 mg/kg) or equimolar doses of ATB-352 (15 or 46 mg/kg). Postoperative pain responses were blindly recorded 1–5 h after administration of the test drugs, as above. At the end of the experiment, the gastric and duodenal mucosae were blindly scored (macroscopically and microscopically) for hemorrhagic damage, as described previously (30).

**Author Disclosure Statement**

David J. Vaughan and John L. Wallace are employees of Antibe Therapeutics, Inc.

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**Abbreviations Used**

ANOVA = analysis of variance
CB = cannabinoid
COX = cyclooxygenase
FAAH = fatty acid amidase hydrolase
GI = gastrointestinal
H$_2$ = histamine receptor-2
H$_2$S = hydrogen sulfide
NSAID = nonsteroidal anti-inflammatory drug