Synergy between Enzyme Inhibitors of Fatty Acid Amide Hydrolase and Cyclooxygenase in Visceral Nociception

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ABSTRACT

The present study investigated whether inhibition of fatty acid amide hydrolase (FAAH), the enzyme responsible for anandamide catabolism, produces antinociception in the acetic acid-induced abdominal stretching model of visceral nociception. Genetic deletion or pharmacological inhibition of FAAH reduced acetic acid-induced abdominal stretching. Transgenic mice that express FAAH exclusively in the nervous system displayed the antinociceptive phenotype, indicating the involvement of peripheral fatty acid amides. The cannabinoid receptor 1 (CB1) receptor antagonist, rimonabant, but not the cannabinoid receptor 2 (CB2) receptor antagonist, SR144528, blocked the antinociceptive phenotype of FAAH(-/-) mice and the analgesic effects of URB597 (3-carboxamyl-biphenyl-3-yl-cyclohexylcarbamate) or OL-135 (1-oxo-1-[5-(2-pyridyl)-2-yl]-7-phenyl heptane), respective irreversible and reversible FAAH inhibitors, administered to C57BL/6 mice. The opioid receptor antagonist, naltrexone, did not block the analgesic effects of either FAAH inhibitor. URB597, ED50 [95% confidence interval (CI)] = 2.1 (1.5–2.9) mg/kg, and the nonselective cyclooxygenase inhibitor, diclofenac sodium, ED50 (95% CI) = 9.8 (8.2–11.7) mg/kg, dose-dependently inhibited acetic acid-induced abdominal stretching. Combinations of URB597 and diclofenac yielded synergistic analgesic interactions according to isobolographic analysis. It is important that FAAH(-/-) mice and URB597-treated mice displayed significant reductions in the severity of gastric irritation caused by diclofenac. URB597 lost its gastroprotective effects in CB1(-/-) mice, whereas it maintained its efficacy in CB2(-/-) mice, indicating a CB1 mechanism of action. Taken together, the results of the present study suggest that FAAH represents a promising target for the treatment of visceral pain, and a combination of FAAH inhibitors and NSAIDs may have great utility to treat visceral pain, with reduced gastric toxicity.

Visceral pain is a major cause of consulting in gastroenterology and the principal symptom of functional bowel disorders. This symptom is often associated with gut hypersensitivity to distension. The endogenous cannabinoid system possesses attractive targets for drugs that could potentially treat visceral and other types of pain. These targets include cannabinoid (i.e., CB1 and CB2) receptors and fatty acid amide hydrolase (FAAH), the enzyme responsible for degradation of the endogenous cannabinoid, anandamide, and other fatty acid amides (Walker and Hohmann, 2005). Direct-acting cannabinoid receptor agonists, such as ∆9-tetrahydrocannabinol (THC), the primary psychoactive constituent of Cannabis sativa, and the irreversible FAAH inhibitor URB597 inhibited visceral nociception, as assessed in the phenyl-p-quinone model (Haller et al., 2006). The antinociceptive effects of both of these compounds were blocked by the CB1 receptor antagonist, rimonabant, indicating a CB1 receptor mechanism of action. Although direct-acting cannabinoid receptor agonists possess analgesic properties similar to those of opioids, but without respiratory depressant effects, their psychomimetic side effects have dampened enthusiasm for their development as analgesics.

ABBREVIATIONS: CB1, cannabinoid receptor 1; CB2, cannabinoid receptor 2; FAAH, fatty acid amide hydrolase; THC, ∆9-tetrahydrocannabinol; URB597, 3-carboxamyl-biphenyl-3-yl-cyclohexylcarbamate; OL-135, 1-oxo-1-[5-(2-pyridyl)-2-yl]-7-phenyl heptane; CNS, central nervous system; NSAID, nonsteroidal anti-inflammatory drug; COX, cyclooxygenase; FAAH-NS, nervous system FAAH-restricted; ANOVA, analysis of variance; 2-AG, 2-arachidonoyl glycerol; SR144528, N-[(1S)-endo-1,3,3,trimethylbicyclo[2.2.1]heptan-2-yl]-5-(4-chloro-3-methylphenyl)-1-(4-methylbenzyl)-pyrazole-3-carboxamide; WIN55,212-2, (R)-[+]-2,3-dihydro-6-methyl-3-(4-morpholinyl)methylpyrrolo-[1,2,3-d,e]-1,4-benzoxazin-6-yl]-1-naphthalenyl-methanone.
therapeutic agents. In contrast, increasing endogenous cannabinoid levels by blocking FAAH represents an attractive alternate approach to elicit antinociception, but without eliciting cannabimimetic effects (Cravatt et al., 2001; Gobbi et al., 2005). Deletion of the FAAH gene leads to increased levels of anandamide, accompanied with CB1 receptor-mediated hypoalgesic phenotypes in models of acute and inflammatory pain (Cravatt et al., 2001). Likewise, wild-type mice treated with FAAH inhibitors, such as URB597 (Kathuria et al., 2003) or the reversible FAAH inhibitor, OL-135 (Lightman et al., 2004a), elicited hypoalgesic effects in acute models of pain that were accompanied with elevations of anandamide in the CNS. In addition, these FAAH inhibitors reduced hypersensitivity to thermal and mechanical hyperalgesia and mechanical hyperalgesia in neuropathic pain models (Chang et al., 2006; Russo et al., 2007).

Nonsteroidal anti-inflammatory drugs (NSAIDs), the mainstays in acute and chronic pain management, produce their beneficial actions by inhibiting cyclooxygenases (COXs): constitutive COX-1 and inducible COX-2 (Warner and Mitchell, 2004), which are responsible for the biosynthesis of the proinflammatory prostaglandins in the periphery (Vinegar et al., 1976) and CNS (Samad et al., 2001). However, the gastrointestinal adverse effects of nonselective COX inhibitors remain a major clinical concern (Wallace, 1996). On the other hand, FAAH deletion or inhibition leads to protective effects in animal models of colitis (Massa et al., 2004; Storr et al., 2008).

Of relevance, coadministration of locally applied anandamide and COX inhibitors produced synergistic antinociceptive effects in the rat formalin test (Guindon et al., 2006) and also offered an attractive therapeutic approach that maintains analgesic efficacy while minimizing untoward side effects associated with direct-acting cannabinoid receptor agonists and the NSAIDs. As a consequence, there were four goals of the present study. First, we examined whether FAAH(−/−) mice or wild-type mice treated with inhibitors of FAAH would display decreased nociceptive behavior in the acetic acid-induced abdominal stretching test. Second, we sought to determine the receptor mechanism of action underlying the antinociceptive phenotype of FAAH-compromised mice. Mice were evaluated with the respective CB1 or CB2 receptor antagonists, rimonabant and SR144528. In addition, because the antinociceptive effects of FAAH inhibitors have been suggested to include an opioid receptor mechanism of action (Chang et al., 2006), we also evaluated whether naltrexone would block the antinociceptive effects of URB597 and OL-135. Third, we used an isobolographic approach to determine whether URB597, given in combination with diclofenac, a nonselective COX inhibitor, would elicit additive or synergistic antinociceptive effects. Fourth, we evaluated whether FAAH inhibition would offer gastroprotective effects against NSAID-induced gastric ulcers.

Materials and Methods

Subjects. The subjects consisted of male C57BL/6J mice (The Jackson Laboratory, Bar Harbor, ME), FAAH(−/−) mice backcrossed for at least 13 generations, CB1(−/−) mice backcrossed for at least 13 generations, and CB2(−/−) mice backcrossed for 5 generations onto a C57BL/6J background. In addition, male and female nervous system FAAH-restricted (FAAH-NS) (Cravatt et al., 2004) mice backcrossed onto a C57BL/6J background for at least 11 generations were used to determine whether the FAAH(−/−) antinociceptive phenotype was due to the deletion of this enzyme from neuronal tissue. All subjects weighed between 20 and 30 g and were housed four mice per cage in a temperature-controlled (20–22°C) facility, with food and water available ad libitum. All animal protocols were approved by the Virginia Commonwealth University Institutional Animal Care and Use Committee and were in concordance with the Guide for Care and Use of Laboratory Animals (Institute of Laboratory Animal Resources, 1996).

Drugs. Diclofenac sodium and naltrexone HCl were purchased from Sigma-Aldrich (St. Louis, MO). URB597 was purchased from Cayman Chemical (Ann Arbor, MI). WIN55,212-2 and ranitidine were purchased from Tocris Bioscience (Ellisville, MO). Rimonabant (CB1 receptor antagonist) and SR144528 (CB2 receptor antagonist) were obtained from the National Institutes of Health National Institute on Drug Abuse (Rockville, MD). All the drugs were dissolved in a vehicle consisting of ethanol, alamkulis-620 (sanofi-aventis, Bridgewater, NJ), and saline in a ratio of 1:1:18, with the exception of naltrexone, which was dissolved in 0.9% saline. Acetic acid (0.6%) was diluted in saline and administered via the intraperitoneal route of administration. All other drugs were administered through the subcutaneous route of administration, with the exception of diclofenac in the gastric tolerability test. The injection volume for acetic acid and each drug was 10 μL/g body weight.

Acetic Acid-Induced Stretching. All animals were acclimated to laboratory environment for at least 2 h before testing. The acetic acid-induced stretching assay was carried out as described previously (Jain et al., 2002). In brief, each mouse was given an intraperitoneal injection of acetic acid. Beginning 3 min after the administration of acetic acid, the number of stretches [constriction of abdomen, turning of the trunk (twist), and extension of the body and hind limbs] per mouse was counted for a 20-min period.

Diclofenac, WIN55,212-2, URB597, or OL-135 were given via the subcutaneous route of administration 60 min before acetic acid administration. In the antagonism studies, rimonabant (3 mg/kg) and SR144528 (3 mg/kg) were given 70 min before acetic acid, whereas naltrexone (1 mg/kg) was administered 30 min before acetic acid. Each of these doses and pretreatment times were based on previous reports from the literature and from previous studies from our laboratory.

Dose-response curves for URB597 and diclofenac were obtained using at least six animals at each dose. Mice were given subcutaneous injections of vehicle, diclofenac (3, 10, or 30 mg/kg), or URB597 (1, 5, or 10 mg/kg) and 60 min later were given an intraperitoneal injection of acetic acid. Dose-response curves were also obtained after coadministration of URB597 and diclofenac (ED50 MIX) in fixed-ratio combinations based on fractions of their respective ED50 values. The ratios of URB597 and diclofenac were 1:3, 1:1, and 3:1 (for specific doses of each drug, see Table 1). In the drug combination experiments, mice received a single injection containing both drugs.

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Test.

Ranitidine, a histamine H2 receptor blocker, was also used as a positive control. The dose and commonly used antiulcer agent, was used as a positive control.

The experimental ulcer induction, the mice were given a single dose of 30 or 100 mg/kg for each drug alone or in combination. To determine the ED50 values, the data were analyzed using two-way ANOVA, one-way ANOVA, or Dunnett's test was used for post hoc analysis in the dose-response experiments. In addition, planned comparisons were used to in the studies examining mechanism of action. The ED50 values with 95% confidence intervals were calculated using standard linear regression analysis of the dose-response curve for each drug alone or in combination. To determine the ED50 values, the data were transformed to percentage maximal possible effect using the following equation: percentage maximal possible effect = 100 × (mean number of stretches in the control group – mean number of stretches in the test group)/mean number of stretches in the control group.

Isobolographic analysis was used to determine the nature of the drug interactions, as described previously (Tallarida, 2000). The dose of diclofenac required to elicit a 50% effect was plotted on the abscissa, and the isoeffective dose of URB597 was plotted on the ordinate. The theoretical additive effect of the two drugs was represented by the straight line connecting the two points. If the experimentally determined data points and their confidence interval lie on this line, the drug effects are considered additive. If the points lie below this line, the interaction is considered to be superadditive (synergistic); however, if they lie above the line of additivity, the interaction is defined as subadditive (antagonistic). To determine whether the interaction between two drugs was synergistic, additive, or antagonistic, the theoretical additive ED50 value of the two drugs combined (referred to as Zadd) was calculated from the dose-response curves of each drug administered individually, in which the combination is assumed to equal the sum of the individual effects of each drug. The experiment ED50 value of the two drugs in combination (referred to as Zmax) in which the two drugs were summed at each concentration was then determined by linear regression. The statistical difference between Zadd (the theoretical ED50 value) and Zmax (the experimental ED50 value) were analyzed using Fisher's test. These calculations were performed using the program of Pharm Tools Pro (version 1.20; The McCary Group Inc., Elkina Park, PA), based on Tallarida (2000).

p Values less than 0.05 were considered significant.

Results

Acetic Acid-Induced Abdominal Stretching. Intrapерitoneal injection of 0.6% acetic acid in saline elicited a curving of the trunk and extension of limbs, which were scored as a stretch. In general, the first stretch occurred between 2 and 5 min after the acetic acid injection in the control mice. Pretreatment with WIN55,212-2 (2 mg/kg), a mixed CB1/CB2 cannabinoid receptor agonist, or diclofenac sodium (30 mg/kg), a nonselective COX inhibitor, significantly reduced the acetic acid-induced abdominal stretches in mice compared with vehicle controls, F(3,16) = 156, p < 0.001 (Fig. 1). However, WIN55,212-2-treated mice showed reductions in locomotor activity, one of many THC-like effects that has been described previously (Compton et al., 1992), thus making it difficult to delineate between antinociception and motor suppression. In contrast, none of the other drugs tested elicited any apparent alterations in behavior.

Receptor Mechanisms Underlying the Antinociceptive Phenotype of FAAH-Compromised Mice. As shown

![Fig. 1. Diclofenac sodium and WIN55,212-2 pretreatment reduces acetic acid-induced visceral nociception. Intrapерitoneal administration of 0.6% acetic acid elicited a significant increase in abdominal stretches in mice. Pretreatment with diclofenac sodium (30 mg/kg s.c.) or WIN55,212-2 (2 mg/kg s.c.) attenuated the number of acetic acid-induced abdominal stretches compared with the vehicle-treated group. ***p < 0.001 versus vehicle-treated group; data depicted as means ± S.E.M., n = 6 to 8 mice/group.](image-url)
in Fig. 2A, FAAH(−/−) mice displayed a significant attenuation of acetic-induced nociception, t(10) = 5.0, p < 0.001. FAAH regulates endocannabinoid pathways in both the central nervous system and peripheral tissues, either of which could regulate nociception. Thus, we next evaluated acetic acid-induced abdominal stretching in transgenic mice that express FAAH exclusively in the nervous system (FAAH-NS mice) (Cravatt et al., 2004). FAAH-NS mice retained the antinociceptive phenotype, F(2,19) = 10.858, p < 0.001 (Fig. 2B), implicating the involvement of nonneuronal endogenous cannabinoids in this phenotype.

Rimonabant and SR144528, respectively, were used to ascertain the involvement of CB1 and CB2 receptors in the antinociceptive phenotype exhibited by FAAH(−/−) mice. Rimonabant (3 mg/kg), but not SR144528 (3 mg/kg), significantly blocked the antinociceptive phenotype of FAAH(−/−) mice, F(2,33) = 6.1, p < 0.01 (Fig. 2C). In contrast, these cannabinoid receptor antagonists administered alone to wild-type mice did not alter the number of abdominal stretches compared with vehicle-treated control mice. These results suggest that the antinociceptive phenotype of FAAH(−/−) mice in the acetic acid model of visceral nociception is mediated through a CB1 cannabinoid receptor mechanism of action.

We next evaluated the effects of URB597, a well studied irreversible FAAH inhibitor (Kathuria et al., 2003), and OL-135, a reversible FAAH inhibitor (Boger et al., 2001), in the acetic acid stretching test. As shown in Fig. 3A, URB597 (10 mg/kg) significantly reduced acetic acid-induced abdominal stretching, F(3,32) = 14.8, p < 0.001. Pretreatment with rimonabant (3 mg/kg), but not SR144528 (3 mg/kg), significantly blocked the antinociceptive effects of URB597. Likewise, administration of OL-135 (30 mg/kg) produced CB1 receptor-mediated antinociceptive effects in the acetic acid model, F(3,20) = 19.4, p < 0.001 (Fig. 3B). As in the case of URB597, pretreatment with rimonabant (3 mg/kg), but not SR144528 (3 mg/kg), significantly blocked the antinociceptive effects of OL-135. The antinociceptive effects of URB597 or OL-135 [main effect of FAAH inhibitor, F(2,30) = 68, p < 0.001] was not blocked by naltrexone (1 mg/kg; see Fig. 3C). Finally, diclofenac sodium (30 mg/kg s.c.) significantly attenuated acetic acid-induced nociception, F(3,16) = 12, p < 0.001. The failure of rimonabant pretreatment to reverse the antinociceptive effects of this drug indicates that the underlying mechanism of action is independent of CB1 receptors (see Fig. 3D). As previously shown in Fig. 2C), rimonabant alone did not affect acetic acid-induced stretching.

**Dose-Response Analysis of URB597 and Diclofenac Sodium Alone and in Combination.** Figure 4A depicts the dose-response curves for the antinociceptive effects of URB597 [F(3,17) = 23, p < 0.001] and diclofenac [F(3,17) = 47, p < 0.001] alone in mice. The ED₅₀ values and 95% confidence limit for URB597 and diclofenac were 2.1 (1.5–2.8) and 9.8 (8.2–11.7) mg/kg, respectively. Shown in Fig. 4B are the 1.3, 1.1, and 3:1 combinations of URB597 and diclofenac, with the dose of URB597 plotted on the abscissa. The dose-response curve of URB597 alone is plotted in this graph for comparison. The same data are also plotted in Fig. 4C, with the dose of diclofenac plotted on the abscissa. The dose-response curve of diclofenac alone is included in this graph for comparison. The plots of the combination ED₅₀ values for both fixed ratios (total dose) in relation to the ED₅₀ values of the drugs alone are shown in Fig. 4D. The isobologram suggests that a synergistic interaction occurs between URB597 and diclofenac because the experimental points lie significantly below the line of additivity. This graphic display of synergism is confirmed mathematically by statistical analysis of the predicted additive ED₅₀ values (Zadd) and experimentally derived ED₅₀ values (Zmix) shown in Table 1.
each ratio tested, the Zmix value is significantly less than the Zadd value.

FAAH(−/−) Mice and URB597-Treated Wild-Type Mice Show Gastroprotective Effects. Because one of the most common adverse effects associated with NSAID treatment is gastric ulcers, we evaluated the impact of FAAH deletion or inhibition on diclofenac-provoked gastric irritation. Diclofenac sodium treatment (100 mg/kg p.o.) caused a significant induction of gastric ulcers compared with saline-treated mice in food restricted mice (Fig. 6A). Pretreatment with the histamine H2 receptor antagonist, ranitidine (50 mg/kg s.c.), as a positive control, significantly reduced diclofenac-induced gastric ulcers, \( F(2,16) = 28, p < 0.001 \). Shown in Fig. 5B are representative illustrations of stomachs from a mouse in each condition. Next, we compared the effects of diclofenac (100 mg/kg) between FAAH(+/+) and (−/−) mice. As can be seen in Fig. 5C, diclofenac provoked less gastric ulceration in FAAH(−/−) mice than in wild-type mice, \( t(14) = 2.2, p < 0.05 \).

In the final series of experiments, we evaluated the effects of URB597 on diclofenac-induced gastric ulcers. Subjects were treated with either vehicle or URB597 (10 mg/kg s.c.) 1 h before diclofenac (0, 30, or 100 mg/kg gavage). Two-way ANOVA revealed a significant interaction between URB597 and diclofenac, \( F(2,40) = 5.9, p < 0.01 \) (Fig. 6A). URB597 significantly reduced the severity of ulcers elicited by both concentrations of diclofenac. Stomachs from representative mice treated with vehicle or diclofenac (30 mg/kg s.c.) and vehicle or URB597 are shown in Fig. 6B. To examine whether the gastroprotective effects of URB597 are mediated through a cannabinoid receptor mechanism, we evaluated this drug in mice lacking CB1 or CB2 receptors. As illustrated in Fig. 6C, URB597 no longer offered gastric protection in CB1(−/−) mice \( (p = 0.50) \), although it continued to reduce ulcer index scores in CB1(+/+) mice \( (p < 0.05) \). Finally, URB597 significantly reduced diclofenac-induced ulcers to an equal magnitude in CB2(−/−) and (+/+) mice, \( F(1,20) = 18.9, p < 0.001 \). In the absence of URB597, diclofenac elicited ulcers of a similar magnitude between CB2(−/−) and (+/+) mice and between CB1(−/−) and (+/+) mice (see Fig. 6, C and D).

Discussion

The first goal of the present study was to test the hypothesis that FAAH is a viable target to reduce visceral nociception. Complementary approaches of pharmacological blockade and genetic deletion of FAAH significantly reduced acetic acid-induced abdominal stretches. These findings are consis-
tent with those of Haller et al. (2006), who showed that URB597 reduced abdominal stretching in the phenyl-

**p**-quione model of visceral nociception. Previous research has also found that FAAH(/H11002/)-H11002/H11002 mice and mice treated with FAAH inhibitors possess elevated levels of anandamide in the CNS and periphery that reduce baseline pain thresholds to noxious thermal and chemical stimuli (Cravatt et al., 2001; Kathuria et al., 2003; Lichtman et al., 2004a). In addition, FAAH-compromised mice have been shown to display antihyperalgesic effects in the carrageenan paw edema model (Lichtman et al., 2004b). Thus, FAAH blockade elicits hypoalgesic effects in a wide range of preclinical pain models.

It is noteworthy that FAAH(/H11002/)-H11002/H11002 mice possess increased brain levels of fatty acid amides, including N-palmitoyl ethanolamine (Cravatt et al., 2001), and the N-acyl taurines (Saghatelian et al., 2006), any of which could contribute to antinociceptive phenotype. In particular, N-palmitoyl ethanolamine has been well described to have anti-inflammatory actions (Mazzari et al., 1996; Conti et al., 2002; Lo Verme et al., 2005). Thus, it is plausible that elevated levels of this or other lipid signaling molecules, in addition to anandamide, may contribute to the antihyperalgesic phenotype observed in FAAH(/H11002/)-H11002/H11002 mice or mice treated with FAAH inhibitors. However, anandamide is the only substrate of FAAH known to bind and activate cannabinoid receptors. Thus, the second objective of the present study was to determine whether cannabinoid receptors mediate the antinociceptive phenotype of FAAH-compromised mice. It is notable that rimonabant, but not SR144528, blocked the antinociceptive phenotype of FAAH(/H11002/)-H11002/H11002 mice and OL-135- or URB597-treated mice. In contrast to the results of Chang et al. (2006), who reported that naloxone blocked the antihyperalgesic effects of OL-135 in rat spinal nerve ligation and thermal injury models, we found no evidence of opioid receptor involvement in the antinociceptive effects of URB597 and OL-135 in the acetic model of visceral nociception. Thus, these results indicate that CB₁ receptors play a critical role in the antinociceptive effects of FAAH blockade.

Although FAAH has been shown to metabolize a second endogenous cannabinoid, 2-arachidonoyl glycerol (2-AG), under certain in vitro conditions (Di Marzo et al., 1999), this enzyme does not seem to play a relevant role in regulating 2-AG (Blankman et al., 2007). Moreover, FAAH(/H11002/)-H11002/H11002 mice do not display cannabinoid effects to exogenous administration of 2-AG, hydrolyze 2-AG in brain and liver homogenates at equivalent rates as wild-type mice, and possess similar levels of 2-AG as wild-type mice (Lichtman et al., 2002). Notwithstanding the fact that the present study did not quantify
specific substrates of FAAH, our overall results are consistent with the hypothesis that anandamide is responsible for the antinociceptive phenotype of FAAH-compromised mice. In addition, acetic acid elicited virtually the identical number of abdominal stretches in mice treated with rimonabant, SR144528, or vehicle, suggesting that endogenous cannabinoids do not tonically modulate basal nociceptive responses in this model. It is noteworthy that there were fluctuations in nociceptive behavior elicited by i.p. acetic acid administration across the different experiments. Several factors that may account for this variability include the variations in the distribution of acetic acid within the peritoneal cavity, individual differences among different lots of mice evaluated at different times, and the number of subcutaneous injections mice received before acetic acid.

The site of action of endocannabinoids in visceral nociception is not well understood. The reduction in pain behaviors seen in FAAH(−/−) mice persisted when FAAH was expressed exclusively under the control of a neuron-specific promoter, suggesting that endocannabinoids were producing their effects through a peripheral site of action. These results are in accordance with other studies showing analgesic effects of cannabinoids after local administration (Guindon and Beaulieu, 2006; Guindon et al., 2006; Jhaveri et al., 2006).

The strategy of combining analgesics of different classes can facilitate patient compliance, simplify prescriptions, improve efficacy without increasing adverse effects, and decrease adverse effects without loss of efficacy (Raffa, 2001). Combination analgesic therapy is especially useful when the selected drugs have different mechanisms of action that provide additive or synergistic efficacy, reducing the required doses of the individual drugs compared with monotherapy and potentially limiting side effects. In accordance, the third goal of the present study was to determine whether combined administration of an FAAH inhibitor and a COX inhibitor would produce additive or synergistic antinociceptive actions in the acetic acid model of visceral nociception. Using an isobolographic analysis, our results revealed a synergistic antinociceptive interaction between the FAAH inhibitor, URB597, and the NSAID, diclofenac sodium. Thus, administration of a combination of FAAH and COX inhibitors can reduce the amount of drugs required to produce analgesic effects.

However, the isobolographic approach does not provide insight into the mechanism of action underlying this interaction. Although the mechanism of action underlying the synergistic interaction between diclofenac and URB597 is beyond the scope of the present study, it may be related to pharmacokinetic and/or pharmacodynamic factors. The NSAIDs elicit analgesia by inhibiting COX, the enzyme responsible for the biosynthesis of prostaglandins (Vane, 1971). In contrast, the antinociceptive effects caused by FAAH blockade were probably caused by elevated levels of anandamide acting at CB1 receptors. The combination of URB597 and diclofenac would simultaneously block the production of prostaglandins in the viscera and activate CB1 receptor-mediated antinociceptive pathways. In addition, several studies have found that a variety of NSAIDs, including indomethacin and ibuprofen, inhibit FAAH, particularly at low pH that occurs in inflamed tissues (Holt et al., 2001, 2007). However, NSAIDs only inhibit FAAH at considerably high concentrations with EC50 values greater than 50 μM, although it should be noted that diclofenac has not been evaluated in FAAH activity assays. The failure of rimonabant to reverse the antinociceptive effect of diclofenac sodium rules out the involvement of CB1 receptors for this NSAID. Conversely, other targets (e.g., CB2, transient receptor potential vanilloid type 1, or peroxisome proliferator-activated receptor α receptors) that are activated by substrates of FAAH may contribute to the interaction between these two drugs. Finally, the interactions are likely to involve peripheral and central pathways. Although the NSAIDs act mainly through peripheral inhibition of COX, a central action has also been described previously (Miranda et al., 2003). Likewise, cannabinoids have central and peripheral sites of action (Walker and Hoehmann, 2005; Agarwal et al., 2007). In future studies, it will be of value to assess the degree to which FAAH inhibitors and COX inhibitors given alone and in combination reduce the inflammation caused by acetic acid in the viscera. In addition, it will be important to examine whether the syne-
gistic interaction between diclofenac and URB597 extends to other pain models, and assess whether combinations of other FAAH inhibitors and other COX inhibitors produce similar effects.

A synergistic interaction for the antinociceptive effects of FAAH and COX inhibitors is highly appealing; however, this beneficial effect would be nullified, if combined administration of these drugs increases the magnitude of adverse effects. Gastric ulcers are the most frequently associated side effects with NSAID therapy and are generally related to dose. Therefore, the fourth objective of the present study was to determine whether pretreatment with URB597 would significantly reduce NSAID-induced gastric ulcers.

FAAH inhibitors are the most frequently associated side effects with NSAID therapy and are generally related to dose. Therefore, the fourth objective of the present study was to determine whether pretreatment with URB597 would significantly reduce NSAID-induced gastric ulcers. FAAH(-/-) and URB597-treated wild-type mice displayed a significant amelioration in the magnitude of gastric irritation caused by diclofenac given via gavage in fasted mice. These findings are consistent with studies reporting that genetic deletion or pharmacological blockade of FAAH makes mice resistant to experimentally induced colitis (Massa et al., 2004; Storr et al., 2008). Our observations that CB1(-/-) mice, but not CB2(-/-) mice, were resistant to the gastroprotective effects of URB597 suggests that both the antinociceptive and gastroprotective effects caused by FAAH blockade are mediated by CB1 receptors. These findings, taken together, indicate that the combination of URB597 and diclofenac sodium not only shows a synergistic antinociceptive effect but also can significantly reduce a serious adverse effect of the NSAIDs.

In summary, we report that pharmacological inhibition or genetic deletion of FAAH produces CB1 receptor-mediated antinociceptive effects in the acetic acid model of visceral nociception. Coadministration of URB597 and diclofenac sodium elicited a synergistic antinociceptive effect in this assays. Moreover, FAAH(-/-) mice and C57BL/6 mice treated with URB597 displayed a reduction in the caustic effects of diclofenac on the gastric mucosa. The observations that URB597 retained its efficacy in CB2(-/-) and was ineffective in CB1(-/-) mice indicates its gastroprotective effects were mediated through a CB1 mechanism of action. In conclusion, the combination of FAAH inhibitors with NSAIDs may be particularly advantageous in maximizing antinociceptive effects, while minimizing gastric irritation.

Fig. 6. URB597 attenuates diclofenac sodium-induced ulcers through a CB1 receptor mechanism of action. A, pretreatment with URB597 (10 mg/kg s.c.) significantly attenuated diclofenac sodium-induced (30 or 100 mg/kg gavage) gastric ulcers. B, representative stomachs from vehicle-vehicle (top left; score = 0), diclofenac (30 mg/kg)-vehicle (top right; score = 6), vehicle-URB597 (bottom left; score = 0), and diclofenac (30 mg/kg)-URB597 (bottom right; score = 3). C, CB1(-/-) mice were resistant to the gastroprotective effects of URB597 in mice treated with diclofenac sodium (100 mg/kg gavage). D, URB597 ameliorated diclofenac sodium-induced (100 mg/kg gavage) gastric ulcers to a similar magnitude in CB1(+/+) and (-/-) mice. p < 0.05 or **, p < 0.01 compared with corresponding control mice; n = 6 mice/group. Data depicted as mean ± S.E.M. ulcer index.