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Modulation of neuropathic and inflammatory pain by the endocannabinoid transport inhibitor AM404

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ABBREVIATIONS: CCI, chronic constriction injury; Cox-2, cyclooxygenase-2; iNOS, inducible nitric oxide synthase; AM404, N-(hydroxyphenyl)-5Z,8Z,11Z,14Z,-eicosatetraenamide, UCM707, (N-(3-furylmethyl)-eicosa-5,8,11,14-tetraenamide); CFA, complete Freund's adjuvant.

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ABSTRACT

The endocannabinoid system may serve important functions in the central and peripheral regulation of pain. In the present study, we investigated the effects of the endocannabinoid transport inhibitor AM404 [*N*-(4-hydroxyphenyl)-eicosa-5,8,11,14-tetraenamide] on rodent models of acute and persistent nociception (intraplantar formalin injection in the mouse), neuropathic pain (sciatic nerve ligation in the rat) and inflammatory pain (complete Freund's adjuvant injection in the rat). In the formalin model, administration of AM404 (1-10 mg·kg⁻¹, intraperitoneal, i.p.) elicited dose-dependent antinociceptive effects, which were prevented by the CB₁ cannabinoid receptor antagonist rimonabant (SR141716A; 1 mg·kg⁻¹, i.p.), but not by the CB₂ antagonist SR144528 (1 mg·kg⁻¹, i.p.) or the vanilloid antagonist capsazepine (30 mg·kg⁻¹, i.p.). Comparable effects were observed with UCM707 [*N*-(3-furylmethyl)-eicosa-5,8,11,14-tetraenamide], another anandamide transport inhibitor. In both the chronic constriction injury (CCI) and complete Freund's adjuvant (CFA) model, daily treatment with AM404 (1-10 mg·kg⁻¹, subcutaneous, s.c.) for 14 days produced a dose-dependent reduction in nocifensive responses to thermal and mechanical stimuli, which was prevented by a single administration of rimonabant (1 mg·kg⁻¹, i.p.) and was accompanied by decreased expression of cyclooxygenase-2 (Cox-2) and inducible nitric oxide synthase (iNOS) in the sciatic nerve. The results provide new evidence for a role of the endocannabinoid system in pain modulation and point to anandamide transport as a potential target for analgesic drug development.

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INTRODUCTION

The endocannabinoids, anandamide and 2-arachidonoylglycerol (2-AG), are removed from the extracellular space by a high-affinity transport system present both in neural and non-neural cells (Beltramo et al, 1997; Hillard et al, 1997). The molecular identity of this putative transporter is still unknown, but some of its biochemical and pharmacological properties have been characterized (for review, see Hillard and Jarrahian, 2003). These include stereoselective substrate recognition and saturation at 37°C, independence from ion gradients, and pharmacological inhibition by agents such as AM404 [*N*-(4-hydrophenyl)-eicosa-5,8,11,14-tetraenamide], UCM707 [*N*-(3-furylmethyl)-eicosa-5,8,11,14-tetraenamide] and LY2183240 (5-biphenyl-4-ylmethyl-tetrazole-1-carboxylic acid dimethylamide) (Beltramo et al, 1997; Piomelli et al, 1999; Lopez-Rodriguez et al., 2001; Moore et al., 2005). After reuptake, anandamide is hydrolyzed by fatty-acid amide hydrolase (FAAH) (Cravatt et al, 1996), an intracellular membrane-bound serine hydrolase whose activity is selectively inhibited by the compounds URB597 (cyclohexylcarbamic acid 3'-carbamoylbiphenyl-3-yl ester) and OL-135 (1-oxo-1-[5-(2-pyridyl)oxazol-2-yl]-7-phenylheptane) (Kathuria et al, 2003; Lichtman et al, 2004) as well as by a variety of non-selective agents (for review, see Piomelli, 2005). Intracellular 2-AG is hydrolyzed by monoacylglycerol lipase (MGL) (Stella et al, 1997; Dinh et al, 2002), which is inhibited by the compounds URB602 [(1,1' -biphenyl)-3-yl-carbamic acid, cyclohexyl ester] (Hohmann et al, 2005; Makara et al, 2005).

Pharmacological blockade of FAAH activity elicits modest, but significant antinociceptive effects in rats (Kathuria et al, 2003; Lichtman et al, 2004), while mutant mice in which the *faah* gene has been deleted by homologous recombination (FAAH^{-/-} mice) are less responsive to acute noxious stimuli than are their wild-type littermates (Cravatt et al, 2001), suggesting that endogenously released anandamide may modulate pain

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sensitivity. This hypothesis is further supported by two observations. First, intraplantar formalin injection and electric foot-shock administration stimulate the release of anandamide and 2-AG in the rat periaqueductal gray (PAG), a key pain-processing structure of the midbrain (Walker et al., 1999; Hohmann et al, 2005). Second, the CB₁ cannabinoid antagonist rimonabant (SR141716A) enhances nocifensive responses in some pain models (Calignano et al., 1998; Strangman et al., 1998)), albeit not in others (Beaulieu et al., 2000), and abrogates the non-opioid component of stress-induced analgesia (Hohmann et al, 2005).

The findings outlined above raise the possibility that inhibitors of anandamide internalization, which prevent the access of anandamide to intracellular FAAH and prolong the duration of action of this endocannabinoid mediator (Beltramo et al, 1997; Kathuria et al, 2003; Fegley et al., 2004), may also have analgesic properties. To test this possibility, in the present study we have investigated the effects of the anandamide transport inhibitor AM404 in models of acute and persistent pain (mouse formalin test), neuropathic pain (rat CCI test) and inflammatory pain (rat CFA test).

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MATERIALS AND METHODS

Animals. We used male Swiss mice (20-25 g, Charles River) for the formalin test and male Wistar rats (200–220 g, Charles River) for all other experiments. The procedures met National Institutes of Health guidelines for the care and use of laboratory animals, those of the Italian Ministry of Health (D.L. 116/92), and were approved by the local Institutional Animal Care and Use Committees.

Drugs. AM404 and capsazepine were obtained from Tocris Cookson (Avonmouth, UK); UCM707 from Cayman Chemical (Ann Arbor, MI); rimonabant and SR144528 from the National Institute on Drug Abuse; all other chemicals were from Sigma Aldrich (St. Louis, MO). Fresh drug solutions were prepared immediately before use in a vehicle of sterile saline/DMSO (80/20, for single administrations) or sterile saline/polyethylene glycol/Tween 80 (90/5/5, vol/vol, for repeated administrations). The i.p. route was selected for single AM404 administrations, and the s.c. route for repeated administrations.

Formalin model. We allowed Swiss mice to acclimate to the testing room for at least 12 h before experiments. We injected formalin (5% formaldehyde in sterile saline, 10 μ l) into the plantar surface of the left hind-paw using a 27-gauge needle fitted to a microsyringe, and immediately transferred the animals to a transparent observation chamber. Nocifensive behavior (licking and biting of the injected paw) was monitored continuously for a period of 45 min divided into two intervals: phase I: 0-15 min; and phase II: 15-45 min (Dubuisson and Dennis, 1977).

CCI model. The sciatic nerve of Wistar rats was surgically ligated as described (Bennett and Xie, 1988). Briefly, the animals were anesthetized with ketamine (100 mg·kg⁻¹, i.p)

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and xylazine (5 mg·kg⁻¹, i.p.). The left sciatic nerve was exposed at mid-thigh level through a small incision, and one-third to one-half of the nerve thickness was loosely ligated with 4 silk threads. The wound was closed with muscle suture and skin clips and dusted with streptomycin powder. In parallel surgeries, the nerve was exposed but not ligated (sham-operated rats). Behavioral tests were performed on the before day of surgery (day -1) and again on days 7 and 14 following surgery.

CFA model. We administered CFA (Sigma Aldrich) in a vehicle of paraffin oil/mannide monooleate (85/15, vol/vol; 0.1 ml) by intradermal injection into the left hind-paw of Wistar rats, using a 27-gauge needle fitted to a microsyringe, on three separate days (1, 3 and 7)(Billingham et al, 1990). Behavioral tests were performed before the first CFA injection (day -1) and again on day 14 of treatment.

Mechanical hyperalgesia. We measured mechanical hyperalgesia using a Randall-Selitto analgesimeter (Ugo Basile, Varese, Italy). Latencies of paw withdrawal to a calibrated pressure were assessed on both ligated and controlateral paws on day -1 (before ligation or CFA treatment), and again on days 7 and 14. Cut-off force was set at 150 g.

Thermal hyperalgesia. We measured thermal hyperalgesia using a Hargreaves apparatus (Hargreaves et al., 1988) (Ugo Basile). Two days before the experiment, the animals were placed in a transparent Perspex box with a thin glass floor and allowed to acclimate for 10-15 min. A focused beam of radiant heat applied to the plantar surface and latencies of paw withdrawal were assessed on both ligated and controlateral paws on day -1 (before ligation or CFA treatment), and again on day 7 and 14. Cut-off time was set at 1 min.

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Rotarod test. Integrity of motor function was assessed in CCI rats using an accelerating rotarod (Ugo Basile). The animals were acclimated to acceleration in 3 training runs. Mean performance time (s) determined on the fourth and fifth run served as control value. Performance time was measured every 20 min for a total of 80 min on days 7 and 14 after surgery.

Immunoblot analyses. CCI, sham-operated and naïve rats were killed and the sciatic nerves from ligated paws were removed and immediately frozen in liquid N₂. Frozen tissue was weighed and homogenized on ice in lysis buffer (Tris-HCl 20 mM pH 7.5, 10 mM NaF, 150 mM, NaCl, 1% Nonidet P-40, 1 mM phenylmethylsulphonyl fluoride, 1 mM Na₃VO₄, leupeptin and trypsin inhibitor 10 µg·ml⁻¹; 0.25 ml per 50 mg tissue). After 1 h, tissue lysates were centrifuged at 100,000xg for 15 min at 4°C, and protein content of the supernatant was measured using bovine serum albumin (Sigma Aldrich) as a standard. Supernatant samples (0.1 mg of protein) were dissolved in Laemmli's buffer, boiled for 5 min, and subjected to SDS-PAGE (8% polyacrylamide). Proteins were transferred onto nitrocellulose membranes (Protran Nitrocellulose Transfer Membrane Schleicher & Schuell Bioscience, Dassel, Germany), blocked with phosphate-buffered saline (PBS) containing 5% non-fat dried milk for 45 min at room temperature, and incubated at 4°C, overnight in the presence of commercial antibodies for iNOS (BD Biosciences Transduction Laboratories, Lexington, KY; dilution 1:2000) or Cox-2 (Cayman; dilution 1:1500) in PBS containing 5% non-fat dried milk, 0.1% Tween 20. The secondary antibody (anti-mouse IgG, or anti-rabbit IgG peroxidase conjugate) was incubated for 1 h at room temperature. Blots were washed with PBS, developed using enhanced chemiluminescence detection reagents (Amersham Pharmacia, Piscataway, NJ) following manufacturer's instructions, and exposed to X-Omat film (Eastman Kodak

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Co., Rochester, NY). Protein bands for iNOS (~130 kDa) and Cox-2 (~72 kDa) were quantified using a model GS-700 imaging densitometer (Bio-Rad Laboratories). An anti- α -tubulin antibody (Sigma Aldrich; dilution 1:1000) was used as a control.

Statistical analyses. Results are expressed as the mean \pm s.e.m. of *n* experiments. All analyses were conducted using Statistica (Statsoft, Tulsa, USA). The significance of differences between groups was determined by t-test, one- or two-way analysis of variance (ANOVA) followed by a Bonferroni post hoc test for multiple comparisons.

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RESULTS

Antinociceptive effects of AM404 in the formalin model

Systemic administration of AM404 (1-10 mg·kg⁻¹, i.p.) in Swiss mice produced a dose-dependent reduction in phase-I nociceptive behavior (Fig. 1a) ($F_{3,32} = 15.08$, $p < 0.0001$; $n = 8$), which was likely dependent on endocannabinoid-mediated activation of CB₁ receptors since it was prevented by the CB₁ antagonist rimonabant (1 mg·kg⁻¹, i.p.), but not by the CB₂ antagonist SR144528 (1 mg·kg⁻¹, i.p.) (Fig. 1c) ($F_{5,50} = 31.72$, $p < 0.0001$; $n = 8$) or the vanilloid antagonist capsazepine (30 mg·kg⁻¹, i.p.; all drugs given 30 min before AM404, $n = 8$) (Fig. 1d) ($F_{3,23} = 16.06$, $p < 0.0001$; $n = 8$). In contrast with its ability to reduce formalin-induced phase-I nociception, AM404 failed to alter phase-II nociception at any of the doses tested (Fig. 1b). This lack of effect might be accounted for by enzymatic degradation (Fegley et al., 2004). Consistent with this possibility, we found that UCM707 (10 mg·kg⁻¹, i.p.), an anandamide transport inhibitor that is partially resistant to enzymatic hydrolysis (Lopez-Rodriguez et al., 2001), significantly reduced both phase-I and phase-II nociception (Fig. 2) ($T = 6.016$, $p < 0.0001$ and $T = 2.553$, $p < 0.05$; $n = 8$).

Antihyperalgesic effects of AM404 in the CCI model

The ability of AM404 to reduce nociception in the formalin test prompted us to investigate the impact of this agent in the CCI model of neuropathic pain (Bennett and Xie, 1988). In an initial test, we measured the effects of a single injection of AM404 on the nocifensive response to thermal stimuli. When administered on day 7 after ligation of

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the sciatic nerve, AM404 (1-10 mg·kg⁻¹, s.c.) produced a modest antihyperalgesic effect, which was significant at the dose of 10 mg·kg⁻¹ (Fig. 3a) ($F_{4,55} = 14.68$, $p < 0.0001$; $n = 12$). At this dose, AM404 did not change nocifensive responses to thermal stimuli applied to contralateral, non-operated paws (vehicle, 6.9 ± 0.3 s; AM404, 7.2 ± 0.4 s; $n = 6$). Next, to determine whether the antihyperalgesic effect of AM404 could be enhanced by repetitive administration, we subjected neuropathic or sham-operated rats to a 14-day regimen with AM404 (1-10 mg·kg⁻¹, s.c., once daily) or vehicle. AM404 produced a reduction in both thermal (Fig. 3b) and mechanical hyperalgesia (Fig. 3c), compared to vehicle ($F_{3,372} = 18.08$ for treatment, $F_{3,372} = 17.71$ for time and thermal hyperalgesia; $F_{3,372} = 13.20$ for treatment, $F_{3,372} = 123.8$ for time and thermal hyperalgesia $p < 0.0001$; no significant treatment x time interactions, $F_{9,372} = 5.410$; $n = 32$). These effects were significant at 10 mg·kg⁻¹ (Fig. 3b-c) and were prevented by a single injection of the CB₁ antagonist rimonabant, but not the CB₂ antagonist SR144528 (Fig. 4)(each drug at 1 mg·kg⁻¹, i.p., 30 min before AM404) ($F_{3,324} = 31.84$ for treatment, $F_{3,324} = 14.13$ for time and thermal hyperalgesia; $F_{3,324} = 21.75$ for treatment, $F_{3,324} = 71.55$ for time thermal hyperalgesia $p < 0.0001$ $n = 24-32$).

As expected, CCI rats displayed a marked disruption in motor function, as assessed in the rotarod test (Fig. 5) ($F_{2,33} = 14.77$, $p < 0.0001$, $n = 12$). This deficit was significantly ameliorated either by acute AM404 administration (10 mg·kg⁻¹, s.c.) (Fig. 5a) or subchronic AM404 treatment (10 mg·kg⁻¹, s.c., once daily for 7 or 14 days) (Fig. 5b) ($F_{2,33} = 54.63$ for treatment, $p < 0.0001$, $F_{1,33} = 0.9888$ $p > 0.05$ for time, $n = 12$). By contrast, AM404 (10 mg·kg⁻¹, s.c., once daily for 7 or 14 days) exerted no significant effect in sham-operated rats (rotarod latency; day 7: vehicle, 102.5 ± 5.9 s; AM404, 97.1 ± 4.6 s; day 14: vehicle, 103 ± 4.7 s; AM404, 104 ± 4 s). These results indicate that the

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antihyperalgesic actions of this agent may not be ascribed to sedation or motor impairment.

Effects of AM404 on Cox-2 and iNOS expression in the CCI model

To further investigate the antihyperalgesic properties of AM404, we asked whether this endocannabinoid transport inhibitor alters expression of Cox-2 and iNOS, two enzymes that have been implicated in the pathogenesis of neuropathic pain (Bingham et al., 2005; De Alba et al., 2005). As previously reported (Levy et al., 1999), immunoblot analyses revealed that sciatic nerve extracts from CCI rats contained significantly higher levels of immunoreactive Cox-2 and iNOS than did extracts from either naïve or sham-operated animals (Fig. 6). Importantly, daily administration of AM404 (3 and 10 mg·kg⁻¹, s.c.) for 7 or 14 days decreased levels of both proteins in a dose-dependent manner (Fig. 6). In particular, the 14-day regimen with AM404 almost normalized Cox-2 and iNOS expression levels, reducing them to values comparable to those measured in sham-operated rats (Fig. 6).

Antihyperalgesic effects of AM404 in the CFA model

Finally, we examined the ability of AM404 to attenuate hyperalgesic responses in the CFA model of arthritis (Billingham, 1990). We treated rats with CFA and then subjected them to a 14-day regimen with AM404 (1-10 mg·kg⁻¹, s.c., once daily) or vehicle. AM404 produced a dose-dependent reduction in both thermal (Fig. 7a) and mechanical hyperalgesia (Fig. 7b), compared to vehicle. These effects were prevented by a single injection of rimonabant, but not SR144528 (each drug at 1 mg·kg⁻¹, i.p., 30 min before

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AM404)($F_{8,263} = 12.19$, $p < 0.0001$ for thermal hyperalgesia; $F_{8,271} = 6.373$, $p < 0.0001$ for mechanical hyperalgesia; $n=24-32$).

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DISCUSSION

The main finding of the present study is that the endocannabinoid transport inhibitor AM404 exerts significant antinociceptive and antihyperalgesic effects in three mechanistically distinct rodent models of pain – the formalin model of acute and persistent nociception (Dubuisson and Dennis, 1977), the CCI model of neuropathic pain (Bennett and Xie, 1988), and the CFA model of arthritis-induced pain (Billingham, 1990). These effects are prevented by the CB₁ antagonist rimonabant, but not by CB₂ and vanilloid antagonists, suggesting that they are caused by endocannabinoid-mediated activation of CB₁ receptors. Notably, the analgesic actions of AM404 cannot be attributed to sedation, since they are accompanied by an improvement rather than an impairment of motor activity in the rotarod test, and are associated with a marked reduction in the expression of Cox-2 and iNOS, two proteins that are involved in the pathogenesis of neuropathic pain and inflammation (Levy et al., 1999; De Alba et al., 2005).

A large body of evidence indicates that direct-acting cannabinoid agonists reduce nocifensive behaviors in animals and alleviate pain in humans by activating cannabinoid receptors. In animals, systemic or intracerebral administration of cannabinoid agonists produces profound antinociceptive effects and suppresses activity in CB₁-expressing nociceptive neurons of the thalamus, midbrain and brainstem (Hohmann et al., 1995; Meng et al., 1998; Hohmann et al., 1999; Hohmann et al., 2005). Likewise, neuropathic pain patients orally treated with the synthetic cannabinoid agonist CT-3 reported significantly less pain than did placebo-treated patients (Karst et al., 2003). In addition to these central effects, cannabinoid agonists may also prevent formalin-evoked pain

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responses in mice (Calignano et al., 1998) and capsaicin-evoked pain in monkeys and human volunteers (Ko and Woods, 1999; Rukwied et al, 2003) presumably by interacting with CB₁ or CB₂ receptors localized on sensory neuron terminals or resident non-neural cells (Hohmann and Herkenham, 1999; Nackley et al., 2004; Ibrahim et al., 2005).

The results outlined above suggest that AM404 may produce its analgesic effects by blocking endocannabinoid transport, thus magnifying endocannabinoid-mediated modulation of pain sensitivity. Three lines of evidence provide further support for this possibility. Firstly, CB₁ receptor blockade enhances pain behaviors in several pain models (Calignano et al., 1998; Strangmann et al., 1998; but see Beaulieu et al., 2000 for contrasting results) and abrogates non-opioid stress-induced analgesia (Hohmann et al, 2005), suggesting the existence of an analgesic endocannabinoid tone. Secondly, administration of AM404 increases endogenous anandamide levels in the mouse brain (Fegley et al., 2004) and decreases cFOS immunoreactivity in the dorsal superficial laminae of the spinal cord in CCI rats (Rodella et al., 2005). Thirdly, genetic deletion or pharmacological inhibition of FAAH elevates brain anandamide levels and reduces nocifensive behaviors in mice and rats (Cravatt et al, 2001; Kathuria et al., 2003; Lichtman et al, 2004). Finally, the non-aliphatic anandamide transport inhibitor LY-2183240 – though structurally unrelated to AM404 and UCM707 – exerts significant antinociceptive effects in the formalin model (Moore et al., 2005). It is worth noting, however, that while LY-2183240 and UCM707 inhibit both first and second phase of formalin nociception, AM404 only inhibits the former. This discrepancy might be accounted for by the known sensitivity of AM404 to enzymatic degradation (Fegley et al., 2004), but current information on the pharmacological properties of UCM707 and LY-

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2183240 is too limited to allow us to exclude the possibility that these compounds may act through alternative non-cannabinoid mechanisms.

Previous studies have shown that AM404 does not closely reproduce the pharmacological profile of direct-acting cannabinoid agonists (Beltramo et al, 2000, Fegley et al, 2004). This difference has been attributed to the ability of AM404 to inhibit endocannabinoid transport without directly activating CB₁ receptors (Beltramo et al, 1997; 2000). Recently, the existence of endocannabinoid transport has been questioned in favor of a simple diffusion mechanism, whereby anandamide accumulation may be solely driven by an inward concentration gradient maintained by FAAH-mediated hydrolysis (Glaser et al, 2003). In this context, the actions of AM404 have been ascribed to its ability to serve as a FAAH substrate and to compete with anandamide for FAAH activity. However, the discovery that pharmacological or genetic inactivation of FAAH does not affect anandamide internalization in neurons strongly argues against this possibility and in favor of the transporter hypothesis (Kathuria et al., 2003; Fegley et al, 2004; Ortega-Gutierrez et al, 2004). Additional support to this hypothesis comes from the recent discovery of potent non-aliphatic inhibitors of endocannabinoid transport, which has led to the identification of a high-affinity binding site presumably involved in the transport process (Moore et al, 2005).

In addition to its inhibitory action on anandamide transport, AM404 binds *in vitro* to several unrelated pharmacological targets, such as vanilloid TRPV1 receptors and sodium channels (Piomelli, 2005). Although the *in vivo* significance of these effects is still unclear, we cannot rule out that some of the observed effects might depend on non-specific actions of AM404. Nevertheless, the ability of the CB₁ antagonist rimonabant, but not the vanilloid antagonist capsazepine, to prevent the actions of AM404 suggests

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that such actions can be ascribed to endocannabinoid-mediated activation of CB₁ receptors.

Several questions remain unanswered. For example, the identity of the endocannabinoid modulator(s) affected by AM404 treatment and the brain region(s) implicated in its effects are still unknown. Nevertheless, our results do suggest that endocannabinoid transport may provide a valuable target for analgesic drugs, underscoring the need to molecularly characterize this system and to further current efforts to develop a second generation of potent and selective transport inhibitors.

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FOOTNOTES

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FIGURE LEGENDS

Fig. 1. Antinociceptive effects of the endocannabinoid transport inhibitor AM404 on formalin-induced paw licking in mice. AM404 ($1-10 \text{ mg}\cdot\text{kg}^{-1}$, i.p.) reduced paw licking time in (A) phase I but not (B) phase II (**, $P < 0.01$, ***, $P < 0.001$ compared to vehicle; $n=8$ per group). This effect was prevented by CB_1 antagonist rimonabant (RIM, $1 \text{ mg}\cdot\text{kg}^{-1}$, i.p), but not (C) the CB_2 antagonist SR144528 (SR2, $1 \text{ mg}\cdot\text{kg}^{-1}$, i.p) or (D) the vanilloid antagonist capsazepine (CPZ, $30 \text{ mg}\cdot\text{kg}^{-1}$, i.p.). (**, $P < 0.01$, ***, $P < 0.001$ compared to vehicle; ■ ■ ■, $P < 0.001$ compared to AM404 alone; $n=8$ per group).

Fig. 2. Antinociceptive effects of the endocannabinoid transport inhibitor UCM707 on formalin-induced paw licking. UCM707 ($10 \text{ mg}\cdot\text{kg}^{-1}$, i.p.) reduced licking time in both (A) phase I and (B) phase II (*, $P < 0.05$, **, $P < 0.01$, compared to vehicle; $n=8$ per group).

Fig. 3. Antihyperalgesic effects of AM404 in the rat CCI model of neuropathic pain. (A) Effects of single AM404 injections ($1-10 \text{ mg}\cdot\text{kg}^{-1}$, i.p.) on thermal hyperalgesia. (B,C) Effects of repeated AM404 injections ($1-10 \text{ mg}\cdot\text{kg}^{-1}$, s.c., once daily for 3-14 days) on (B) thermal and (C) mechanical hyperalgesia. (● ●, $P < 0.01$ vs sham; *, $P < 0.05$, ***, $P < 0.001$ vs. CCI-vehicle; $n= 12-32$ per group)

Fig. 4. The CB_1 antagonist rimonabant prevents the effects of AM404 in the rat CCI model. Effects of single injections of rimonabant (RIM, $1 \text{ mg}\cdot\text{kg}^{-1}$, i.p.) or SR144528 (SR2, $1 \text{ mg}\cdot\text{kg}^{-1}$, i.p.) on the effects of subchronic AM404 ($10 \text{ mg}\cdot\text{kg}^{-1}$, s.c., once daily for 3-14 days) on (A) thermal and (B) mechanical antihyperalgesia. (***, $P < 0.001$ vs. CCI vehicle; ■■■, $P < 0.01$ vs. AM404 alone; $n= 24-32$ per group).

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Fig. 5. Effects of AM404 on motor function in CCI rats. (A) Effect of single injections of AM404 (10 mg·kg⁻¹, i.p.) or vehicle. (B) Effect of repeated injections of AM404 (10 mg·kg⁻¹, i.p., once daily for 7 or 14 days) or vehicle. (● ●, *P*<0.01, vs Sham; *, *P*<0.05, **, *P*<0.01 vs. CCI vehicle; *n*= 12 per group).

Fig. 6. Effects of AM404 on immunoreactive Cox-2 and iNOS in the sciatic nerve of CCI rats. (A, B) Effects of subchronic treatment with AM404 (3 or 10 mg·kg⁻¹, s.c., once daily for 7 or 14 days) on Cox-2 levels: (A) representative immunoblots; (B) densitometric quantification (filled bars represent AM404-treated) (C, D) Effects of subchronic treatment with AM404 (3 or 10 mg·kg⁻¹, s.c., once daily for 7 or 14 days) on iNOS levels: (C) representative immunoblots; (D) densitometric quantification (filled bars represent AM404-treated). Equal loading was confirmed by α -tubulin staining. (● ●, *P*<0.01, ● ● ●, *P*<0.001 vs Sham; **, *P*<0.01, ***, *P*<0.001 vs CCI vehicle; *n*=6 rats per group).

Fig. 7. Antihyperalgesic effects of AM404 in the rat CFA model of arthritic pain. Effects of subchronic treatment with AM404 (1-10 mg·kg⁻¹, s.c., once daily for 14 days) on (A) thermal and (B) mechanical hyperalgesia. Rimobabant (RIM, 1 mg·kg⁻¹, i.p.) but not SR144528 (SR2, 1 mg·kg⁻¹, i.p.) prevented these effects. (*, *P* < 0.05, **, *P* < 0.01, ***, *P* < 0.001 compared to vehicle; ■ ■ ■, *P* <0.001 compared to AM404 alone; *n*=12 per group).

Fig.1

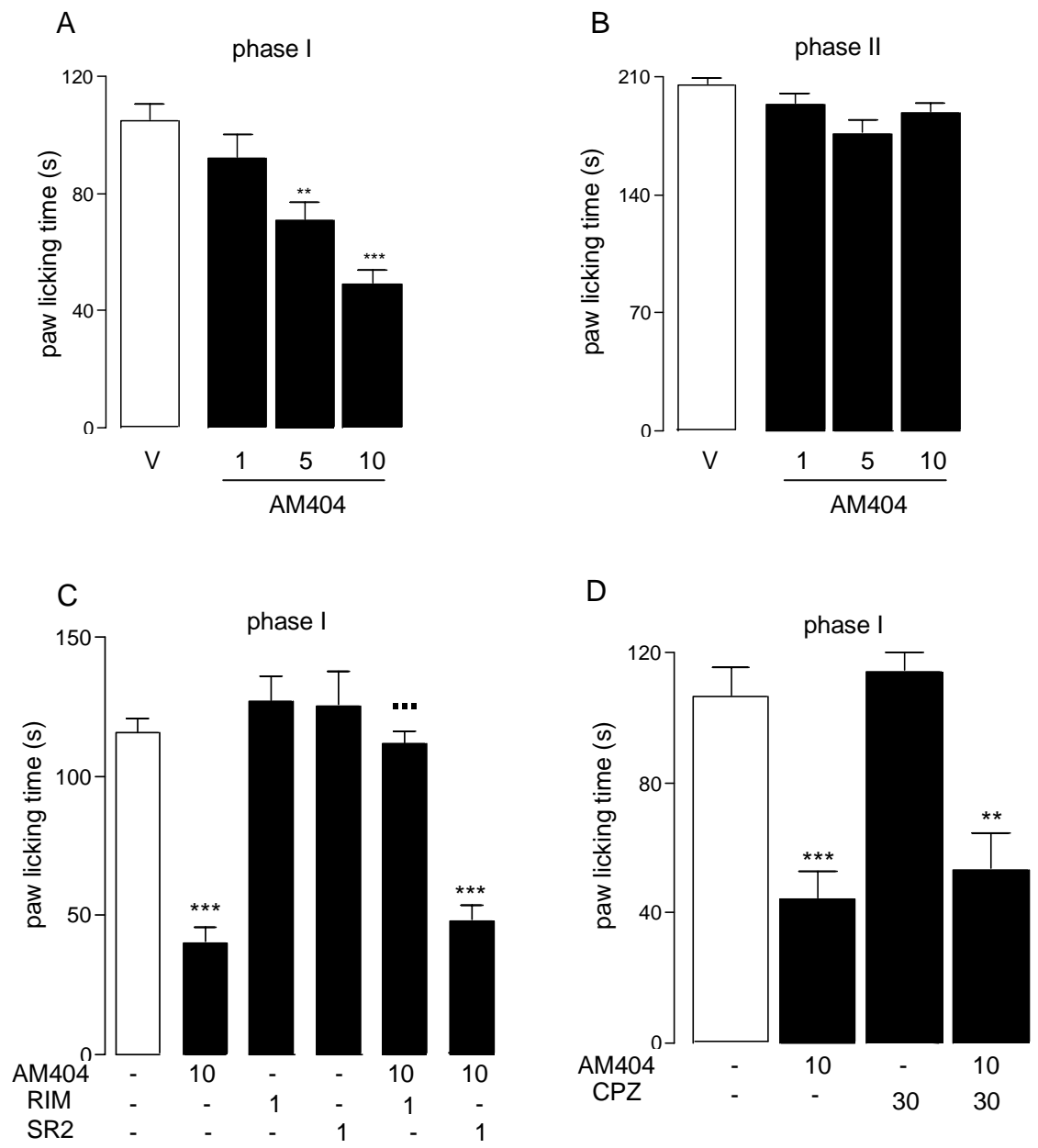


Fig. 2

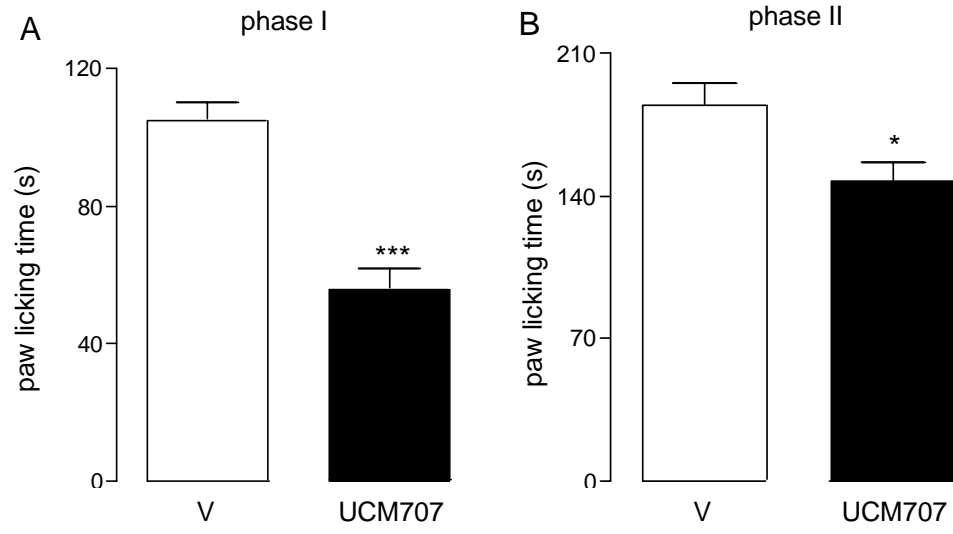


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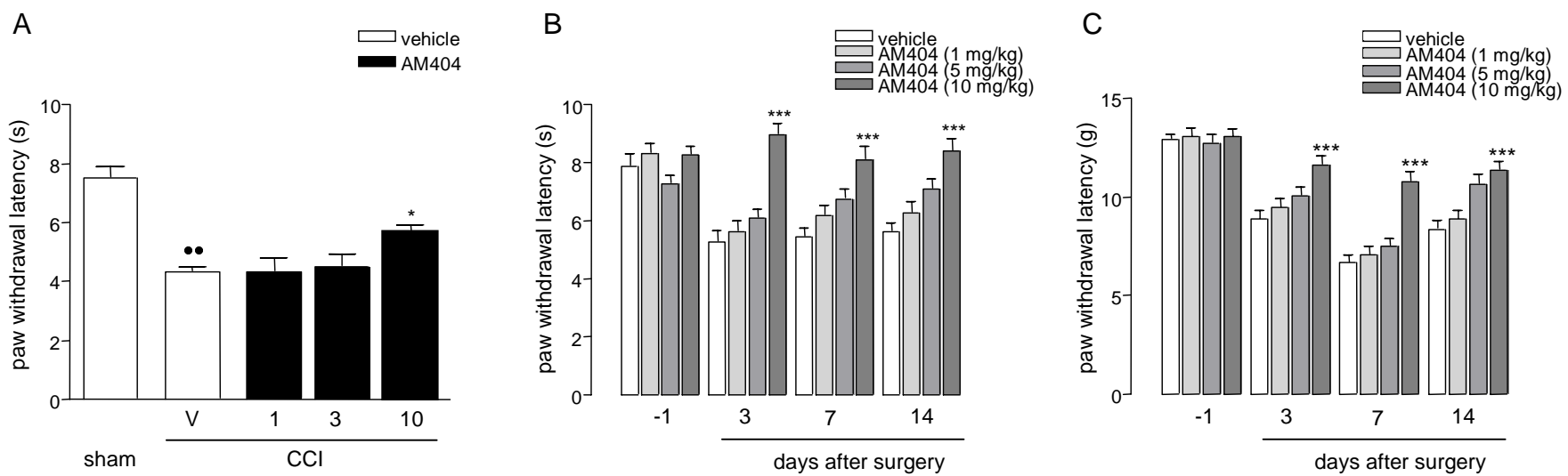


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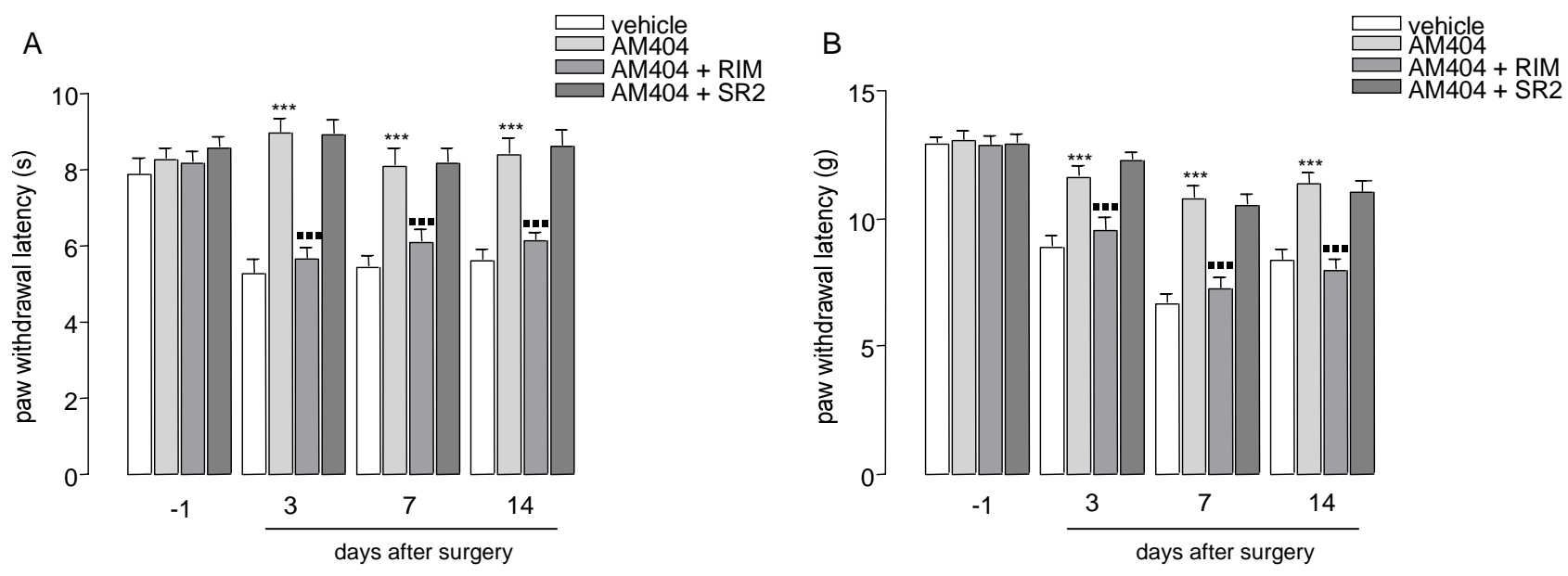


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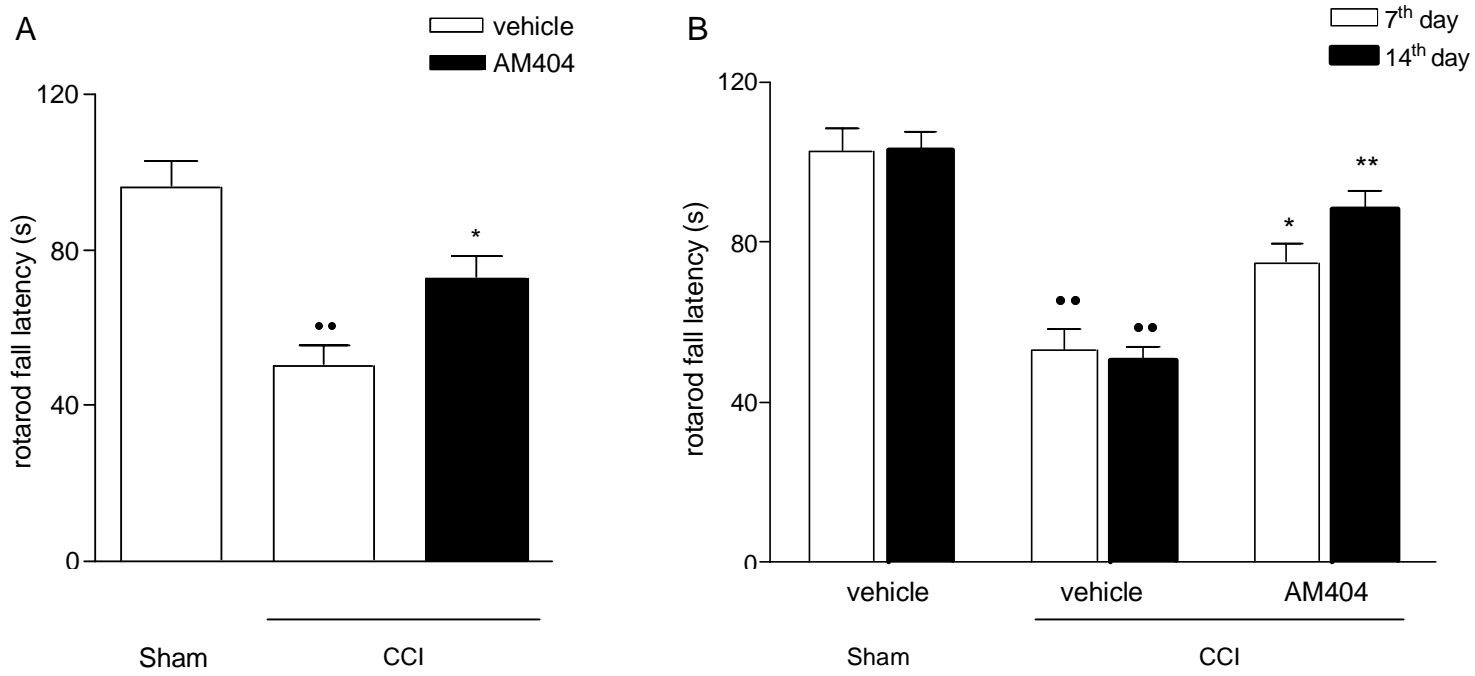


Fig. 6

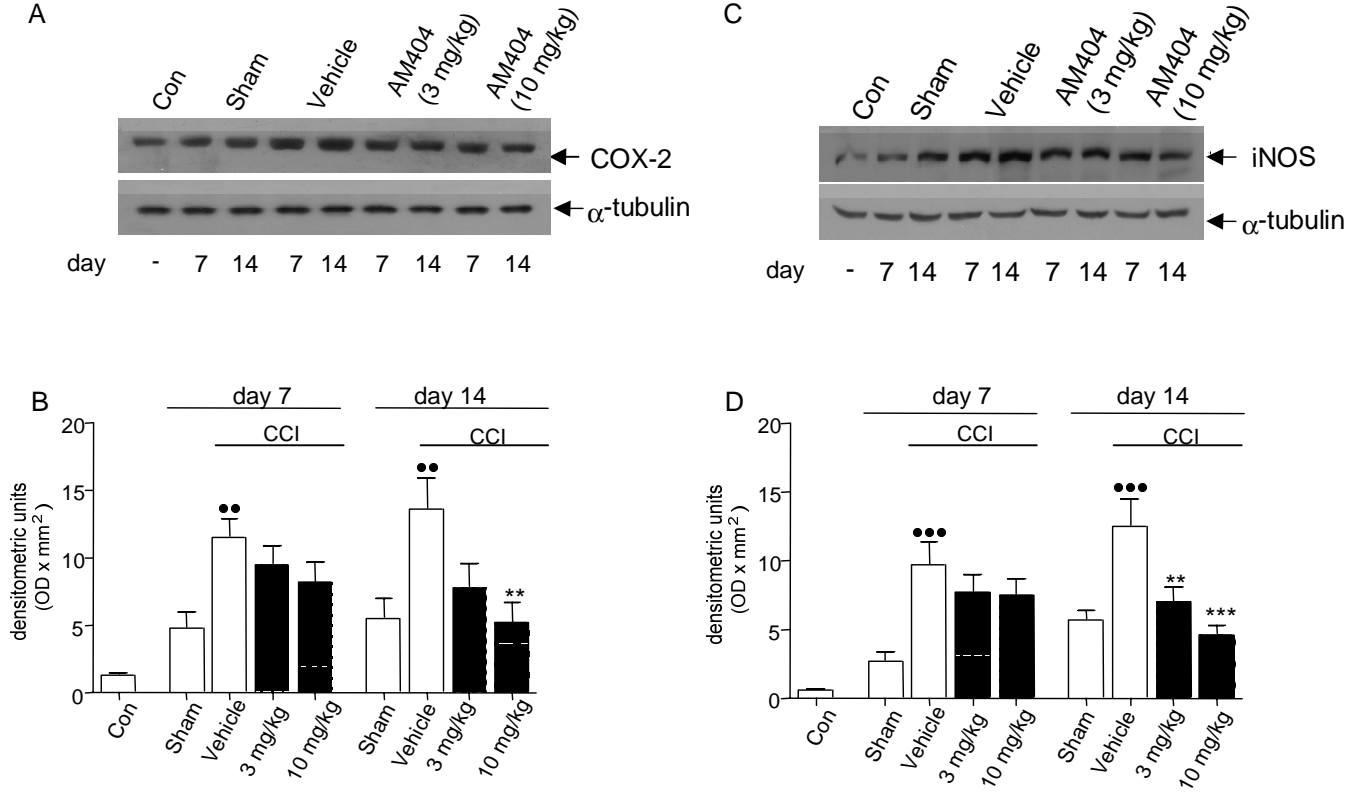


Fig. 7

