Monoamine-dependent, opioid-independent antihypersensitivity effects of intrathecally administered milnacipran, a serotonin noradrenaline reuptake inhibitor, in a postoperative pain model in rats

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Abstract

The neurotransmitters serotonin (5-HT) and noradrenaline (NA) have important roles in suppressing nociceptive transmission in the spinal cord. In the present study, we determined the efficacy and nature of the antihypersensitivity effects of milnacipran, a 5-HT and NA reuptake inhibitor (SNRI), in the spinal cord in a rat model of postoperative pain. Sprague-Daley rats were used in all experiments. An incision was made on the plantar aspect of the hind paw. Mechanical hypersensitivity was measured by determining the withdrawal threshold to von Frey filaments applied to the paw. Drugs were administered intrathecally 24 h after paw incision. Microdialysis studies of the dorsal horn of the lumbar spinal cord were also performed to measure 5-HT and NA levels after systemic injection of milnacipran. Milnacipran (1-30 µg) produced dose-dependent antihypersensitivity effects. The effect lasted 6 h after the 30-µg injection. Doses of 30 µg or less produced no abnormal behavior. The peak antihypersensitivity effect of 10 µg milnacipran was blocked by intrathecal pretreatment with antagonists of the α2-adrenoceptor (idazoxan, 30 µg) or 5-HT receptors (methysergide, 30 µg). Intrathecal pretreatment with 30 µg naloxone, a μ-opioid receptor antagonist, did not reverse the effect of milnacipran. Isobolographic analysis indicated antinociceptive synergism between milnacipran and morphine. Microdialysis studies revealed that milnacipran increased both 5-HT and NA levels in the spinal dorsal horn. These findings suggest that the antihypersensitivity effect of intrathecal milnacipran in the postoperative pain model is monoamine-mediated. Combined administration of an SNRI with morphine might be a promising treatment to suppress postoperative hypersensitivity.
Introduction

Bulbospinal descending noradrenaline (NA) and serotonin (5-HT) systems suppress nociceptive signals from primary afferent neurons to the spinal dorsal horn neurons. Intrathecal administration of adrenoceptor agonists and 5-HT receptor agonists produces antinociceptive effects on acute pain in rodents (Yaksh and Wilson, 1979; Reddy et al., 1980) and suppresses allodynia in a rat model of neuropathic pain (Yaksh et al., 1995; Obata et al., 2001). Antidepressants have antinociceptive effects and are widely used for the treatment of chronic pain. Antidepressants might inhibit chronic pain in the spinal cord by blocking NA or 5-HT reuptake (Sindrup et al., 2005). Among antidepressants, tricyclic antidepressants (TCAs) and 5-HT and NA reuptake inhibitors (SNRIs) are recommended for the management of neuropathic pain (Dworkin et al., 2007). The mechanisms of the antinociceptive effects of TCAs are complicated. TCAs inhibit the reuptake of NA and 5-HT at neuronal terminals (Sindrup et al., 2005). TCAs have antagonistic action at N-methyl-D-aspartate (NMDA) receptors (Reynolds and Miller, 1988), and inhibit adenosine reuptake (Phillis et al., 1982). Further, most TCAs have affinity for opioid (Isenberg et al., 1984), NA, 5-HT, histamine, and muscarinic acetylcholine receptors (Hall and Ögren, 1981). In contrast, SNRIs selectively inhibit the reuptake of NA and 5-HT without relevant affinity for any other receptors or ion channels (Sindrup et al., 2005). One representative SNRI is milnacipran, which is used to treat fibromyalgia (Gendreau et al., 2005; Mease et al., 2009). This type of agent might produce antinociceptive effects in the spinal cord for other types of pain hypersensitivity.

Postoperative pain represents an unmet medical need, because pain during the first days after surgery is rated as intense or very intense in one of every two patients (Chauvin, 1999). Several approaches have been used to reduce postoperative pain, including administration of systemic opioids and nonsteroidal anti-inflammatory drugs, epidural or
spinal infusion of local anesthetics, and peripheral nerve block. Despite the relative efficacy of these current analgesic strategies, a vast number of patients still develop persistent or chronic pain after surgery, and the intensity of acute postoperative pain correlates with the risk of developing a persistent pain (Kehlet et al., 2006). Therefore, new strategies to prevent postoperative pain should be further investigated. Postoperative pain in humans can be mimicked by paw incision in rats (Brennan et al., 1996). Emerging literature suggests that mechanisms of hypersensitivity after paw incision differ from those following inflammatory or peripheral nerve injury (see discussion). We hypothesized that reuptake inhibition of NA and 5-HT in the spinal cord inhibits postoperative pain. To test this hypothesis, we evaluated the antinociceptive potency and efficacy of intrathecally administered milnacipran in the paw incision model of postoperative pain.

Another purpose of the study was to investigate the mechanism of the antinociceptive effect of intrathecally administered milnacipran. Thus, antagonists for $\alpha_2$-adrenoceptors, 5-HT receptors, and muscarinic receptors were used to antagonize the antinociceptive effect of milnacipran. Aditionally, several lines of evidence suggest that the antinociceptive effect of antidepressants is due to their interaction with opioidergic systems (Ardid and Guilbaud, 1992; Gray et al., 1998). Whether this interaction also occurs in the spinal cord, however, is not clear. Therefore, we also investigate the antidepressant-opioidergic system interaction in the spinal cord, first by examining the effect of $\mu$-opioid receptor antagonism on the action of milnacipran, and second by determining whether milnacipran and morphine interact in an additive or synergistic manner based on isobolographic analysis. Finally, NA and 5-HT levels in the spinal cord after milnacipran injection were evaluated by in vivo microdialysis studies.
Methods

Surgical preparation.

The study was approved by the Animal Care and Use Committee of the Gunma University School of Medicine (Maebashi, Japan). Male Sprague-Dawley rats (250 g) were used in all experiments. Animals were housed under a 12-h light-dark cycle, with food and water ad libitum. For intrathecal administration, a sterilized 32-gauge polyethylene catheter (RecathCo, Allison Park, PA) connected to 8.5-cm Tygon external tubing (Saint-Gobain Performance Plastics, Akron, OH) was inserted under halothane anesthesia, as previously described (Yaksh and Rudy, 1976). The catheter was passed caudally 7.5 cm from the cisterna magnum to the lumbar enlargement. Only animals without evidence of neurologic dysfunction after catheter insertion were used for studies. Paw incision, described by Brennan et al. (1996), was performed 5 d after intrathecal catheter implantation. Briefly, rats were anesthetized with halothane, and after sterile preparation with 70% ethanol, a 1-cm long incision was made in the plantar aspect of the left hind paw, starting 0.5 cm from the edge of the heel toward the toe. The plantaris muscle was elevated and incised longitudinally. The wound was closed with 2 mattress sutures using 5.0 silk.

Behavioral Testing.

Rats were placed individually in a plastic cage with a plastic mesh floor, and allowed to acclimate to the environment for 20 min. Withdrawal threshold was determined using calibrated von Frey filaments (Stoelting, Wood Dale, IL), beginning with the 2.0-grams filament. Filaments were applied vertically to an area adjacent to the wound for 6 s, using just enough pressure to gently bend the filament. In the absence of a response, a filament of the next greater force was applied. In the presence of a response, a filament of the next lower
force was applied. The tactile stimulus producing a 50% likelihood of withdrawal was determined using the up-down method, as described by Chaplan et al (1994). General behavior, including ambulation and activity level, was assessed throughout the testing period. The investigator was blinded to the drug treatment for all studies.

Drugs and their administration.

Drug testing was performed 24 h after the paw incision. Rats received intrathecal milnacipran (1, 3, 10, 30 µg) or morphine (1, 3, and 10 µg). The withdrawal threshold was determined before (prepaw incision threshold) and 24 h after incision (baseline), then at 15, 30, 60, 90, 120 min and at 60 min-intervals thereafter for 6 h after intrathecal injection using the up-down method with von Frey filaments. Antagonist studies were performed to test whether the effect of milnacipran in the postoperative pain model involved α2-adrenergic receptors (idazoxan), 5-HT receptors (methysergide), muscarinic receptors (atropine), and μ-opioid receptors (naloxone). Saline or 30 µg of each antagonist was administered intrathecally 15 min prior to milnacipran injection. The dose of the antagonist was selected according to previous studies (Obata et al., 2005b). Drugs were administered intrathecally in a volume of 5 µl, followed by a 10 µl of saline injection to flush the catheter. All drugs were dissolved in normal saline. Milnacipran was donated by the Asahi Kasei Corporation (Osaka, Japan). Other drugs were purchased from Sigma Chemical Co. (St. Louis, MO).

Dose-response curves were generated from the peak effect at each dose after conversion of withdrawal thresholds to percentages of maximum possible effect (%MPE), where %MPE = 100 × (postdrug response – baseline)/(prepaw incision threshold – baseline). The area under the time-course curves (AUC) for the %MPE were then calculated from individual scores at each time point using the trapezoidal rule and divided by the maximum
score that could be obtained over the observation period (% maximum possible AUC).
Isobolographic analysis was performed to determine the type of interaction between milnacipran and morphine. The dose producing a 50% MPE (ED50) was calculated from dose-response curves for each drug that reduced postoperative hypersensitivity. For drug combination dose responses, a fixed-ratio combination of milnacipran and morphine was administered. The fixed ratio combination was based on the ratio of the ED50 value of milnacipran and morphine (1:0.018 w/w).

Microdialysis studies.

Microdialysis studies were performed with normal rats and rats with paw incision (24 h after incision). Anesthesia was induced with urethane (1.2-1.5 g/kg, intraperitoneal), and maintained with 0.5 % isoflurane in 100% oxygen through a nose cone. The left femoral vein was cannulated for drug injections. Rectal temperature was maintained at 37-38°C by a heating pad placed beneath the animal. The L3-L5 level of the spinal cord was exposed by a thoraco-lumbar laminectomy, and the rat was placed into a stereotaxic apparatus. After opening of the dura, a dorsal root that enters the spinal cord above the level of the recording sites was lifted using a glass retractor, so that a microdialysis probe could be advanced into the superficial layer of the dorsal horn. The probe was inserted from just lateral to the dorsal root and advanced at a 15º angle to a depth of 1 mm using a micromanipulator (model WR-88, Narishige, Japan). The surface of the spinal cord was covered with mineral oil. Microdialysis probes were composed of a 1-mm length of hairpin-shaped dialysis membrane (OD = 0.22 mm, ID = 0.20 mm), and the membrane was attached to a 1-cm-silica double lumen tube (OD = 0.35 mm; Eicom Co., Kyoto, Japan). The microdialysis probe was perfused with Ringer’s solution (147 mM NaCl, 4 mM KCl, 2.3 mM CaCl2) at a constant flow rate (1 μl/min) using a
syringe pump (ESP-64, Eicom Co.). After 120 min of constant perfusion, two consecutive samples were collected to determine basal NA and 5-HT concentrations in the dialysate. Milnacipran was administered intravenously to stably increase the drug concentration in the spinal cord. Saline (0.5 ml) or milnacipran (10 mg/kg) was administered through a femoral vein cannula and the 15-min perfusate fractions were collected into an auto injector (EAS-20, Eicom Co.). Samples (15 μl) were automatically injected and analyzed for NA and 5-HT concentration using high-performance liquid chromatography with electrochemical detection by an HTEC-500 analyzing system (Eicom Co.). The chromatographic conditions were as follows: the mobile phase consisted of 0.1 M ammonium acetate buffer (pH 6.0) and methanol (7:3 v/v) containing 0.05 M sodium sulfonate, and 50 mg/l EDTA-2Na. The column was a EICOMPAC CAX (2.0 mm × 200 mm; Eicom Co.). The detection limit of the assay is under 30 fg per injection (Eicom Co.).

Statistics.

Data from behavioral and microdialysis studies were normally distributed and are shown as mean ± SEM. The time-course data were analyzed using a two-way analysis of variance (ANOVA). Post hoc tests were completed for between-group comparisons at time points using a Student-Newman-Keuls post-hoc test for multiple comparisons. A one-way ANOVA, followed by a Student-Newman-Keuls post-hoc test was used for comparison of AUCs. The ED50 was calculated by linear regression analysis. The isobolograms were constructed as previously described (Tallarida et al., 1989). In isobolographic analysis, the theoretical additive points lie on a line connecting the ED50 values of the each drug. Experimental values that lie on or near that line are considered to be generated by additive interactions. Values that lie below and to the left of this additive line are considered to be
synergistic, whereas values that lie above and to the right of that line demonstrate a less than additive interaction. The difference between the theoretical additive point and the experimentally determined value was compared using the Student’s t test. A $P$ value of less than 0.05 was considered to indicate statistical significance.
Results

Behavioral studies.

Intrathecal administration of milnacipran (1-30 μg) produced antihypersensitivity effects in a dose-dependent manner ($P < 0.01$ by two-way ANOVA, Fig. 1). The threshold increased within 15 min and a peak effect was attained approximately 30 min after injection. The effect continued for 6 h after administration of 30 μg when compared to the saline-treated group ($P < 0.05$). No adverse behavioral effects, such as motor effects, sedation, or agitation, were observed. The antihypersensitivity effect of 10 μg milnacipran administered intrathecally was attenuated by idazoxan ($P < 0.01$, Fig. 2B). Although methysergide attenuated the peak effect of milnacipran ($P < 0.01$, Fig. 2A), it did not decrease the AUC of 10 μg milnacipran (Fig. 2B). Intrathecal administration of idazoxan and methysergide alone at these doses produced slight agitation, but did not alter the withdrawal threshold, which was 5.4 ± 0.5 g before idazoxan with a nadir of 4.9 ± 0.7 g after idazoxan, or 5.6 ± 0.5 g before methysergide with a nadir of 5.0 ± 0.8 g after methysergide. Neither atropine nor naloxone affected the antihypersensitivity effect of 10 μg milnacipran (Fig. 2).

Intrathecal administration of morphine also produced a dose-dependent antihypersensitivity effect at doses from 0.03 to 0.3 μg, and the effect of the maximum dose of morphine was completely reversed by intrathecal pretreatment with naloxone ($P < 0.01$ by two-way ANOVA, Fig. 3). The peak antihypersensitivity effects of intrathecal injection of the fixed-ratio combination of the two drugs were observed 30 min after injection (Fig. 4A). Dose responses at the time of peak antihypersensitivity (30 min after injection) for milnacipran, morphine, and their combination are shown in figure 4B. The ED50 (95% confidence interval) for milnacipran was 2.93 (1.93-4.09) μg, and that for morphine was 0.053 (0.018-0.089) μg. The ED50 of their combination was 0.41 μg (the ED50 for milnacipran and
morphine was 0.40 μg and 0.0074 μg, respectively), which was only 27.9% of the theoretical additive total dose (1.47 μg, \( P < 0.05 \)). Isobolographic analysis indicated a synergistic interaction between milnacipran and morphine (Fig. 5).

**Microdialysis study**.

Baseline NA concentration prior to drug injection was not different between normal rats and rats with paw incision (0.64 ± 0.083 pg/15 μl in normal rats, and 0.54 ± 0.058 pg/15 μl in rats with paw incision, respectively). Baseline 5-HT concentrations prior to drug injection were also similar (0.45 ± 0.072 pg/15 μl in normal rats, and 0.40 ± 0.12 pg/15 μl in rats with paw incision, respectively). In the saline-treated group, NA and 5-HT concentrations in the dialysates did not change over time (Fig. 6). In the milnacipran (10 mg/kg intravenous)-treated group, NA concentrations increased within 30 min after the drug injection and reached approximately 300% of the baseline value in normal rats, and the increase continued for more than 4 h after drug injection. The increase in NA concentration was smaller in rats with paw incision as compared to the normal group (\( P < 0.05 \) by two-way ANOVA, Fig. 6A). The concentration of 5-HT also increased, but peaked 30 minutes after drug injection and then gradually decreased within 2 h. There was no difference between the normal and paw incision groups (Fig. 6B).
Discussion

The present study demonstrated that intrathecal administration of the SNRI milnacipran mediated a dose-dependent antihypersensitivity effect in a rat postoperative pain model. The maximum dose of milnacipran (30 μg) produced a long-lasting reversal of hypersensitivity with no adverse behavioral effects. The antihypersensitivity effects were attenuated by intrathecal pretreatment with an α₂-adrenoceptor antagonist. The peak effect of milnacipran was also attenuated by a 5-HT receptor antagonist. Direct measurements of NA and 5-HT from the spinal dorsal horn with microdialysis revealed that milnacipran increased both NA and 5-HT levels. Spinal μ-opioid receptors are not involved in the antihypersensitivity effect of milnacipran. Isoboligraphic analysis revealed that milnacipran interacts synergistically with intrathecal morphine.

Emerging literature suggests that postoperative pain exhibits a unique pharmacology of analgesia compared with other sustained pain models. For example, although spinal N-methyl-D-aspartate (NMDA) receptor antagonists attenuate hypersensitivity in most models of persistent pain, they are not effective for treating hypersensitivity after paw incision (Zahn and Brennan, 1998). In contrast, intrathecal administration of non-NMDA receptor antagonists (Zahn et al, 1998) or NK-1 receptor antagonists (Yamamoto and Sakashita, 1999) are effective. Dorsal horn neurons are sensitized after incision, but this sensitization is completely reversed by intraplantar injection of a local anesthetic (Pogatzki et al., 2002b). Further, although descending facilitation from the rostral ventromedial medulla contributes to behavioral hypersensitivity of diverse animal models of inflammatory and neuropathic pain (Porreca et al., 2002), this mechanism is not involved in the hypersensitivity after incision (Pogatzki et al., 2002a).

The neurotransmitters NA and 5-HT have important roles in suppressing nociceptive
transmission in the spinal cord. Milnacipran is an SNRI with equivalent or slightly preferential inhibitory actions on neuronal reuptake of NA (Moret and Briley 1997; Mochizuki et al., 2002; Vaishnavi et al., 2004). Milnacipran has no relevant affinity for any other receptors tested, including α-adrenergic, 5-HT, histamine, muscarinic acetylcholine, opioid, and NMDA receptors (Mochizuki et al., 2002). Therefore, milnacipran is a suitable probe for examining the role of NA and 5-HT in the central nervous systems. Intrathecal administration of milnacipran effectively reverses nerve-injury induced mechanical hypersensitivity (King et al., 2006; Obata et al., 2005b). The present study is the first to demonstrate that simultaneous reuptake inhibition of NA and 5-HT in the spinal cord reduces hypersensitivity in a model of postoperative pain. Alpha2-adrenergic receptors are implicated in the antinociceptive effect of NA on postoperative pain in the spinal cord (Obata et al., 2005a). In the present study, intrathecal pretreatment with idazoxan, an α2-adrenoceptor antagonist, reversed the effect of milnacipran based on comparisons of the AUCs. Methysergide has affinity for both 5-HT1 and 5-HT2 receptor subtypes (Hamel et al., 1989). We previously demonstrated that 30 μg of methysergide reverses the antihypersensitivity effect of intrathecally administered milnacipran in a neuropathic pain model (Obata et al., 2005b). In the present study, intrathecal pretreatment with methysergide attenuated the peak effect of milnacipran to a similar degree as idazoxan. These findings suggest that the antihypersensitivity effects of intrathecally administered milnacipran mainly rely on increased levels of NA in the spinal cord. Increased 5-HT may also play a role in the early phase of antihypersensitivity effects of milnacipran. This speculation is supported by the observations from the microdialysis studies that 10 mg/kg milnacipran injected intravenously preferentially inhibited NA reuptake in the spinal cord. In the present study, the NA increase after milnacipran injection in the postoperative pain model was smaller than that of normal rats.
This result was contrary to findings in a rat model of neuropathic pain study showing increased basal NA level and noradrenergic axon sprouting in the spinal dorsal horn (Hayashida et al., 2008); however, sensitization and reorganization of the spinal cord are associated not only with neuropathic pain, but also with postoperative pain. One possible cause of the smaller NA increase observed in the postoperative pain model is that disinhibition of the noradrenergic descending inhibitory system may occur after acute activation of the inhibitory system by paw incision.

A previous study demonstrated that muscarinic receptors are involved in the antihypersensitivity effects of intrathecally administered milnacipran in a neuropathic pain model, as atropine completely reversed the effects of milnacipran (Obata et al., 2005b). Activation of the spinal muscarinic receptors produces antinociceptive effects (Eisenach, 1999). The stimulation of cholinergic systems by intrathecal injection of α2-adrenoceptor agonists is widely documented. For example, intrathecal clonidine increases acetylcholine concentrations in the cerebrospinal fluid (De Kock et al., 1997). The reliance of clonidine-induced antinociception on this spinal cholinergic interaction varies between normal and nerve-injured animals. Intrathecal clonidine-induced antinociception to acute thermal stimuli in normal rats is unaffected by intrathecal atropine (Paqueron et al., 2003), but the reversal of hypersensitivity by intrathecal clonidine following nerve-injury is completely blocked by intrathecal atropine (Pan et al., 1999). Intrathecally administered 5-HT receptor agonists also interact with muscarinic receptors to inhibit neuropathic pain (Obata et al., 2003). In the present study, however, intrathecal pretreatment with atropine did not reverse the antihypersensitivity effect of milnacipran in the postoperative pain model. The result is consistent with a previous study showing that antihypersensitivity derived from selective spinal reuptake inhibition of NA is not reversed by intrathecal atropine (Obata et al.,
We speculate that the muscarinic dependency of spinal NA/5-HT inhibitory systems increases progressively from postoperative hypersensitivity to nerve injury-induced chronic hypersensitivity.

Recent studies suggest that the opioidergic system is involved in antidepressant-induced antinociception. For example, several types of systemically administered antidepressants produce antinociception that is reversed by systemically administered naloxone (Ardid and Guilbaud, 1992; Gray et al., 1998). Although direct and indirect actions of antidepressants on opioid receptors are suggested (Ardid and Guilbaud, 1992), the mechanisms and sites of this interaction are not clear. In the behavioral studies, we injected all drugs intrathecally in a small volume of saline (5 µl) to examine spinal mechanisms of milnacipran for postoperative pain. Although we cannot exclude drug effects at brain or dorsal root ganglia locations, drugs mainly act at the spinal level after intrathecal injection (Yaksh and Rudy, 1976). The data from the present study suggest that the antihypersensitivity effect of milnacipran does not involve the opioidergic system, at least in the spinal cord, for two reasons. First, naloxone failed to reverse the antihypersensitivity effect of milnacipran; the dose of naloxone used in the present study (30 µg) was sufficient because pretreatment with naloxone completely reversed morphine-mediated antihypersensitivity. Second, the combination of milnacipran and morphine produced a synergistic interaction. Synergy usually indicates that the two drugs have different final pathways to produce their effect.

Interactions between milnacipran and morphine may also be important for a practical reason. Morphine is administered epidurally or spinally to treat acute pain during the perioperative period (ASA 2004). Because morphine therapy often induces adverse effects such as pruritis, urinary retention, respiratory depression, nausea, and vomiting, the current
observation of synergistic interactions between milnacipran and morphine suggest that the morphine dose, and potentially its adverse effects, could be reduced by the addition of milnacipran.

In conclusion, simultaneous inhibition of NA and 5-HT reuptake in the spinal cord by milnacipran effectively suppressed mechanical hypersensitivity after paw incision in rats. The antihypersensitivity effect of milnacipran in the postoperative pain model depends on monoaminergic, but not opioidergic, systems and differs from its effect in the neuropathic pain model. Isobolographic analysis revealed that milnacipran interacted synergistically with morphine. Therefore, intrathecal or epidural injection of an SNRI combined with morphine might be a promising treatment for postoperative pain.
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Footnotes

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Legends for figures.

Fig. 1. Time-course of the antihypersensitivity effects of intrathecally administered milnacipran in rats 1 d after paw incision surgery. Withdrawal thresholds are expressed as mean ± SEM for 8 rats in each group. *P < 0.05 compared with saline-treated group at each time point (two-way ANOVA).

Fig. 2. Effects of intrathecal pretreatment of idazoxan (IDA), a selective α2-adrenoceptor antagonist; methysergide (MET), a 5-HT receptors antagonist; atropine (ATR), a muscarinic receptor antagonist; and naloxone (NAL), a μ-opioid receptor antagonist on the antihypersensitivity effect of 10 µg of milnacipran. Saline or 30 µg of each antagonist was administered intrathecally 15 min prior to milnacipran injection. Time-course effects (A) and percentages of maximal possible area under the curves (B) are shown. Data are expressed as the mean ± SEM for 8 rats in each group. *P < 0.05 compared with saline-treated group (two-way ANOVA was used in panel A and one-way ANOVA was used in panel B).

Fig. 3. Time-course of the antihypersensitivity effects of intrathecally administered morphine in rats 1 d after paw incision surgery. For the antagonist study, 30 µg of naloxone (NAL) was administered intrathecally 15 min prior to morphine (0.3 µg) injection. Withdrawal thresholds are expressed as mean ± SEM for 8 rats in each group. *P < 0.05 compared with saline-treated group at each time point, #P < 0.05 compared with naloxone-treated group at each time point (two-way ANOVA).

Fig. 4. (A): Time-course of the antihypersensitivity effects of the fixed-ratio of the
combination of milnacipran and morphine in rats 1 d after paw incision surgery. Data are expressed as mean ± SEM for 8 rats in each group. *P < 0.05 compared with a saline-treated group at each time point (two-way ANOVA). (B): Log dose-response curves of effects of intrathecally administered milnacipran, morphine, and their combination on paw incision-induced mechanical hypersensitivity. Peak effects (30 min after injection) were used to calculate percentages of the maximum possible effect (%MPE).

Fig. 5. Isobologram at the 50% maximum effective dose (ED50) for intrathecal milnacipran and morphine. The ED50 value and SEM are shown for each drug alone on the axes. The ED50 value and SEM observed for the fixed-ratio combination was significantly below the theoretical additive line, indicating a synergistic interaction. *P < 0.05 compared with theoretical additive point (Student’s t-test).

Fig. 6. Microdialysis to detect increased spinal noradrenaline (NA: A) and serotonin (5-HT: B) levels. Normal rats (n = 6) or rats with paw incision (n = 6) received intravenous saline or milnacipran (10 mg/kg). Data are presented over time as a percentage of the baseline. *P < 0.05 compared with saline-treated group. #P < 0.05 compared with milnacipran-treated paw incision group (two-way ANOVA).
Fig. 1

The graph illustrates the withdrawal threshold (g) in response to Milnacipran intrathecal injection at various concentrations: 30 μg (open circle), 10 μg (filled circle), 3 μg (triangle), and 1 μg (inverted triangle). Saline is also shown (open square). The y-axis represents the withdrawal threshold (g), and the x-axis represents time (h). Asterisks indicate significant differences compared to the control group.
Fig. 2

A

Mitracipran it 10 μg

% Maximum Possible Effect

Time (h)

B

Mitracipran 10 μg it

% Maximum Possible AUC

+ Saline  + NAL 30 μg  + ATR 30 μg  + MET 30 μg  + IDA 30 μg
Fig. 3

The graph shows the withdrawal threshold (g) over time (h) for different doses of Morphine it and a control saline treatment. The y-axis represents the withdrawal threshold in grams, ranging from 0 to 40. The x-axis represents time in hours, with data points at 0, 1, and 2 hours.

The graph includes the following lines:
- **Morphine it** with doses of 0.3 μg (filled squares), 0.1 μg (open circles), and 0.03 μg (upward triangles).
- **Saline** (filled circles).
- **0.3 μg + NAL 30 μg** (open squares).

The graph indicates statistical significance with symbols: * indicates p < 0.05, and ** indicates p < 0.01.
Fig. 4

A

Milnacipran + Morphine it

- 1.47 µg + 0.0265 µg
- 0.44 µg + 0.00795 µg
- 0.147 µg + 0.00265 µg
- Saline

Withdrawal Threshold (g)

Time (h)

B

- Milnacipran
- Morphine
- Morphine (+ Milnacipran)

% Maximum Possible Effect

Dose (µg)
Fig. 6

A

NA

% of Baseline

Time (h)

B

5-HT

% of Baseline

Time (h)