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Different Effects of Opioid and Cannabinoid Receptor Agonists on C-Fiber-Induced Extracellular Signal-Regulated Kinase Activation in Dorsal Horn Neurons in Normal and Spinal Nerve-Ligated Rats

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ABSTRACT

Nerve injury results in neuropathic pain, a debilitating pain condition. Whereas cannabinoids are consistently shown to attenuate neuropathic pain, the efficacy of opioids is highly controversial. Molecular mechanisms underlying analgesic effects of opioids and cannabinoids are not fully understood. We have shown that the signaling molecule ERK (extracellular signal-regulated kinase) is activated by C-fiber stimulation in dorsal horn neurons and contributes to pain sensitization. In this study, we examined whether opioids and cannabinoids can affect C-fiber-induced ERK phosphorylation (pERK) in dorsal horn neurons in spinal cord slices from normal and spinal nerve-ligated rats. In normal control spinal slices, capsaicin induced a drastic pERK expression in superficial dorsal horn neurons, which was suppressed by morphine (10 μM), the selective μ-opioid receptor agonist DAMGO [[D-Ala2, *N*-Me-Phe4, Gly5-ol]-enkephalin (1 μM)], and the selective CB1 receptor ACEA agonist [arachidonyl-2′-chloroethylamide (5 μM)]. One week after spinal nerve ligation when neuropathic pain is fully developed, capsaicin induced less pERK expression in the injured L_5-spinal segment. This pERK induction was not suppressed by morphine (10 μM) and DAMGO (1 μM) but was enhanced by high concentration of DAMGO (5 μM). In contrast, ACEA (10 μM) was still very effective in inhibiting capsaicin-induced pERK expression. In the adjacent L_4 spinal segment, both DAMGO and ACEA significantly suppressed pERK induction by capsaicin. These results indicate that, after nerve injury, opioids lose their capability to suppress C-fiber-induced spinal neuron activation in the injured L_5 but not in the intact L_4 spinal segment, whereas cannabinoids still maintain their efficacy.

Injury to the nervous system causes neuropathic pain, which is resistant to conventional treatment; e.g., nonsteroid anti-inflammatory drugs (Woolf and Mannion, 1999; Ji and Strichartz, 2004). Increasing evidence indicates that cannabinoids are effective in alleviating neuropathic pain via spinal, supraspinal, and peripheral mechanisms (Zeltser et al., 1991; Ibrahim et al., 2003; Lim et al., 2003; Cravatt and Lichtman, 2004). In contrast, the efficacy of opioid in treating neuropathic pain is controversial. Neuropathic pain has traditionally been considered opioid-resistant to intrathecal opioids, in particular (Lee et al., 1995; Mao et al., 1995; Ossipov et al., 1995). However, some recent clinical (Eisenberg et al., 2005; Raja and Haythornthwaite, 2005) and animal studies (Zhao et al., 2004; Zhang et al., 2005) have shown that opioids [especially μ-opioid receptor (MOR) agonists] can be effective in treating neuropathic pain. These conflicting data may result from differences in the type of nerve injury, route of drug administration, potency and receptor selectivity of the particular opioid agonist, and the methods of measuring neuropathic pain. Opioids are believed to inhibit synaptic transmission in dorsal horn spinal cord neurons via both presynaptic and postsynaptic mechanisms. Presynaptically, opioids reduce transmitter release by blocking *N*-type calcium channels (Glaum et al., 1994; Kohno et al., 2005). Postsynaptically, opioids open G protein-coupled inwardly rectifying

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ABBREVIATIONS: MOR, μ-opioid receptor; ACEA, arachidonyl-2′-chloroethylamide; ANOVA, analysis of variance; CB1, cannabinoid receptor subtype-1; CB2, cannabinoid receptor subtype-2; CCK, cholecystokinin; DAMGO, [D-Ala2, *N*-Me-Phe4,Gly5-ol]-enkephalin; DRG, dorsal root ganglion; ERK, extracellular signal-regulated kinase; pERK, phosphorylated ERK; IR, immunoreactive; MAPK, mitogen-activated protein kinase; SNL, spinal nerve ligation; TRPV1, transient receptor potential subtype-1.

potassium channels, hyperpolarizing the membrane (Yoshimura et al., 1983; Kohno et al., 2005). However, molecular mechanisms underlying analgesic effects of opioid and cannabinoid are not fully understood. It is not clear whether spinal neurons have different sensitivity to cannabinoids and opioids after nerve injury.

The extracellular signal-regulated protein kinase (ERK) is the best-studied member of the MAPK (mitogen-activated protein kinase) family and plays a critical role in intracellular signal transduction, neural plasticity, and inflammatory responses (Ji and Woolf, 2001). Our previous studies have shown that noxious stimulation (e.g., C-fiber activation) can induce ERK phosphorylation (activation) in dorsal horn neurons and that inhibition of this phosphorylation by MAPK kinase inhibitors suppresses tissue injury-induced pain hypersensitivity (Ji et al., 1999; Kawasaki et al., 2004). ERK activation by inflammation is also involved in regulating gene transcription and maintaining persistent inflammatory pain (Ji et al., 2002).

Primary afferent nociceptor terminals release several neurotransmitters and neuromodulators in the spinal cord following noxious stimulation. These include the excitatory amino acid glutamate, the neuropeptide substance P, and the brain-derived neurotrophic factor. Activation of the corresponding *N*-methyl-D-aspartate and metabotropic glutamate receptors, NK-1 receptors, and TrkB receptors in postsynaptic dorsal horn neurons has been implicated not only in the induction of pain sensitization but also in the activation of ERK (Ji and Woolf, 2001; Karim et al., 2001; Lever et al., 2003; Kawasaki et al., 2004). Therefore, ERK activation could be used as a marker of dorsal horn neuron activation following noxious stimulation. Are analgesic effects of opioids and cannabinoids associated with the inactivation of ERK? In the present study, we have investigated the effects of cannabinoids and opioids on capsaicin-induced pERK expression in dorsal horn neurons in normal and nerve-ligated neuropathic pain rats.

Materials and Methods

Animals and Reagents. Male Sprague-Dawley rats (150–200 g) were used under Harvard Medical School Animal Care institutional guidelines. The animal room was artificially illuminated from 7:00 AM to 7:00 PM. The rats were anesthetized with sodium pentobarbital (40–50 mg/kg, i.p). To produce a spinal nerve ligation (SNL), the L_5 transverse process was removed to expose the L_4 and L_5 spinal nerves. The L_5 spinal nerve was then isolated and tightly ligated with 6-0 silk thread (Kim and Chung, 1992). Capsaicin and DAMGO were purchased from Sigma-Aldrich (St. Louis, MO). ACEA was purchased from Tocris Cookson Inc. (Ellisville, MO).

Spinal Cord Slice Preparation. Rat spinal cord slices were prepared as described previously (Ji et al., 1999; Kawasaki et al., 2004; Kohno et al., 2005). In brief, the lumbar spinal cord was removed and immersed in cold Krebs' solution and a 700-μm-thick transverse slice from L_4 or L_5 spinal segment was cut on a vibrating microslicer. The slice was perfused with Krebs' solution saturated with 95% O_2 and 5% CO_2 at 36 ± 1°C for more than 3 h. All of the drugs were applied 10 min before capsaicin stimulation and were present during capsaicin stimulation (3 μM for 5 min). Ten minutes after the capsaicin stimulation, the slices were fixed in 4% paraformaldehyde for 60 min, replaced with 20% sucrose overnight, and cut in a cryostat at 15 μm. Because the surfaces of the slices are likely to be damaged during the preparation, we trimmed the slices (100 μm each side) in a cryostat and collected 20 to 25 serial sections (15 μm thick) only from the middle of the slices. Six to eight nonadjacent sections of these (every third one) were picked for analysis. These sections were then processed for immunofluorescence.

Immunohistochemistry. Spinal sections were processed for immunohistochemistry using the immunofluorescence (Jin et al., 2003; Kawasaki et al., 2004). In brief, spinal sections were blocked with 2% goat serum in 0.3% Triton X-100 for 1 h at room temperature and incubated overnight at 4°C with anti-pERK primary antibody (anti-rabbit, 1:300; Cell Signaling Technology Inc., Beverly, MA). The sections were then incubated with Cy3-conjugated secondary antibody (anti-rabbit, 1:300; Jackson ImmunoResearch Laboratories Inc., West Grove, PA) for 90 min at room temperature following primary antibody incubation. Immunostained slides were examined under a Nikon fluorescence microscope. All of the images were captured with a high-resolution CCD Spot camera (Diagnostic Instruments, Sterling Heights, MI).

Quantification and Statistics. Six to eight nonadjacent sections from the lumbar spinal cord (L_4–L_5) segments were selected, and the numbers of immunoreactive (IR) neurons for pERK in the laminae I–II (Molander et al., 1984) were counted in each section, as described previously (Kawasaki et al., 2004). The numbers of labeled neurons from six to eight sections were averaged for each animal, and four to six rats were included in each group. The data were represented as mean ± S.E.M. The percent inhibition of pERK expression by capsaicin after drug treatment was determined by the formula [100 − 100 × (number of pERK-IR neurons after drug treatment − number of basal pERK-IR neurons)/(number of pERK-IR neurons after capsaicin stimulation alone − number of basal pERK-IR neurons)]. For the calculation of percent inhibition, the basal pERK expression was subtracted because it is not changed after drug treatment (also see Kawasaki et al., 2004). The differences between different groups were compared using ANOVA followed by Fisher's protected least significant difference, and the criterion for statistical significance was $P < 0.05$.

Results

Effects of Opioid and Cannabinoid Receptor Agonists on ERK Activation in the Normal Spinal Cord. We used a rat spinal cord slice preparation (700 μm) in the present study. This preparation offers a reliable condition to study pERK expression (Ji et al., 1999; Lever et al., 2003; Kawasaki et al., 2004). In addition, multiple slices can be prepared from each spinal cord segment and drugs can be applied in a known condition in vitro. The slices were perfused for more than 3 h before stimulation to reduce possible pERK background caused by slice preparation (Ji et al., 1999; Kawasaki et al., 2004). There were very few pERK-IR neurons in control-nonstimulated spinal cord slices (Figs. 1a and 2).

To activate C-fibers, we chose capsaicin rather than electrical stimulation, because 1) electrical stimulation at C-fiber intensity will also activate Aβ- and Aδ-fibers and 2) capsaicin stimulation is much easier to apply. Because the capsaicin receptor TRPV1 (transient receptor potential subtype-1) is only expressed in primary afferent terminals in the superficial dorsal horn, bath application of capsaicin to spinal slices can induce the release of neurotransmitters and neuromodulators (e.g., glutamate, substance P, and brain-derived neurotrophic factor) from TRPV1-expressing primary afferents to activate their postsynaptic receptors, leading to ERK activation in dorsal horn neurons (Kawasaki et al., 2004). A brief exposure of capsaicin (3 μM, 5 min) to spinal slice induced a marked pERK increase in the whole superficial dorsal horn (laminae I–II; Figs. 1b and 2). To identify cell

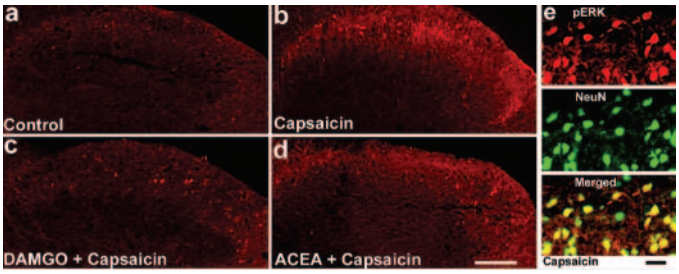

Fig. 1. a to e, pERK immunostaining of nonstimulated spinal cord slices (a) and stimulated slices after treatment with capsaicin (b), capsaicin plus DAMGO (c, 5 μM), and capsaicin plus ACEA (d, 10 μM), obtained from noninjured naive rats. Scale, 100 μm. e, shows colocalization between pERK and NeuN in the superficial dorsal horn after capsaicin stimulation. Scale, 20 μm. The slices (L_4/L_5) were pretreated with DAMGO and ACEA for 10 min followed by capsaicin stimulation (3 μM, 5 min) and then fixed 10 min after capsaicin stimulation for pERK staining.

types exhibiting pERK expression, we performed double immunofluorescence for pERK and NeuN, a neuronal marker. Almost all pERK-labeled cells were also positive for NeuN, indicating that pERK is induced in dorsal horn neurons after capsaicin stimulation (Fig. 1e). There was no significant difference of pERK expression between L_4 and L_5 spinal slices: the number of pERK-positive neurons following capsaicin in the L_4 and L_5 slices was 22.4 $\pm$ 0.8 and 21.9 $\pm$ 1.0 ($n = 4$), respectively.

Capsaicin-induced pERK increase was significantly suppressed by nonspecific MOR agonist morphine (10 μM, 56% inhibition, $P < 0.01$) and by the specific MOR agonist DAMGO (78 and 74% inhibition at 1 and 5 μM, $P < 0.01$; Figs. 1c and 2). The effects of DAMGO were mediated by opioid receptors, because the opioid receptor antagonist naloxone (10 μM) abolished the DAMGO effect; the number of pERK-positive neurons after treatment of naloxone (10 μM) together with DAMGO (5 μM) and capsaicin was 23.6 $\pm$ 2.5 ($n = 4$, $P > 0.05$, compared with capsaicin). However, a high dose of DAMGO (20 μM) did not reduce pERK induction (Fig. 2). A selective CB1 agonist ACEA also inhibited capsaicin-induced pERK expression (41 and 55% inhibition at 5 and 10 μM, respectively, $P < 0.01$; Figs. 1d and 2). Neither DAMGO (5 and 20 μM, 30-min incubation) nor ACEA (10 μM, 30-min incubation) changed the basal expression of pERK (Fig. 2).

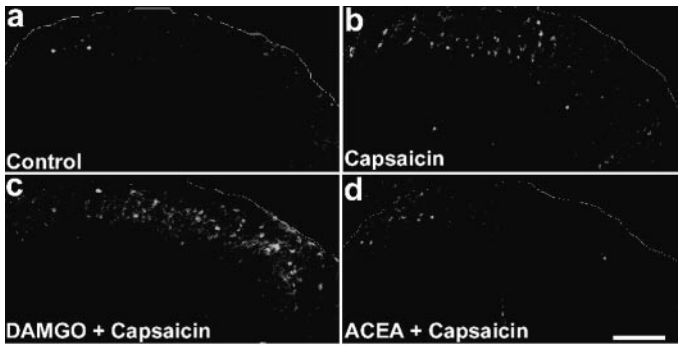

Fig. 3. a to d, pERK immunostaining of nonstimulated spinal cord slices (a) and stimulated slices with treatment of capsaicin (b), capsaicin plus DAMGO (c, 5 μM), and capsaicin plus ACEA (d, 10 μM), obtained from nerve-injured rats at 1 week. Scale, 100 μm. The L_5 slices were pretreated with DAMGO and ACEA for 10 min followed by capsaicin stimulation (3 μM, 5 min). The dotted lines indicate the edges of the dorsal horn gray matter.

These results indicate that both opioid and cannabinoid receptor agonists at optimal concentrations are effective in suppressing C-fiber-induced ERK activation in dorsal horn neurons.

ERK Activation in the Spinal Cord by Capsaicin after Spinal Nerve Ligation. L_5 SNL is known to produce a rapid (<1 day) and persistent (>1 month) neuropathic pain, characterized by mechanical allodynia (nociceptive response to normally innocuous low intensity mechanical stimulus) and heat hyperalgesia (increased response to noxious heat stimulus) (Kim and Chung, 1992). Because nerve injury may change the sensitivity of dorsal horn neurons to cannabinoids and opioids, we further examined the regulation of pERK expression in dorsal horn neurons in the injured L_5 segment and adjacent noninjured L_4 spinal segment at 1 week after SNL when neuropathic pain was fully developed (Kim and Chung, 1992; Jin et al., 2003). The basal pERK level in the laminae I–II of spinal slices was not significantly different from that of control slices from naive rats (naive, 3.1 $\pm$ 0.1; after SNL: L_4, 3.0 $\pm$ 0.2; L_5, 2.9 $\pm$ 0.1). However, pERK induction by capsaicin in the L_5 spinal cord was markedly decreased; the number of pERK-IR neurons decreased from 22.4 $\pm$ 1.0 in naive slices (L_4/L_5) to 12.4 $\pm$ 0.5 ($P < 0.01$) in the L_5 slices of injured rats (Figs. 3–5). This decrease is likely

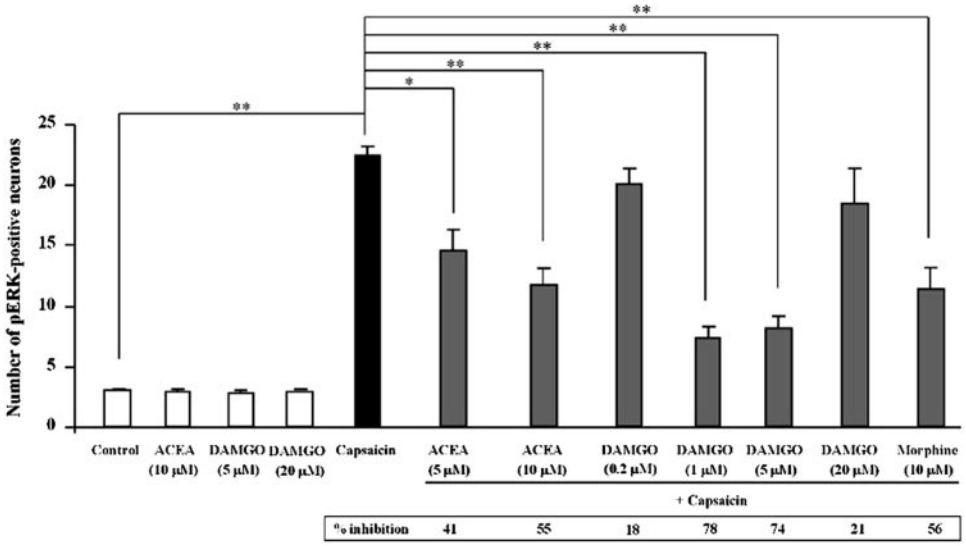

Fig. 2. Quantification of pERK-IR neurons in the superficial dorsal horn (laminae I–II) of spinal slices (L_4/L_5) of noninjured naive rats. Capsaicin (3 μM, 5 min) induces a marked increase in the number of pERK-IR neurons, which is suppressed by DAMGO, morphine, and ACEA at certain concentrations. *, $P < 0.05$; **, $P < 0.01$, ANOVA. Mean $\pm$ S.E.M. ($n = 5$).

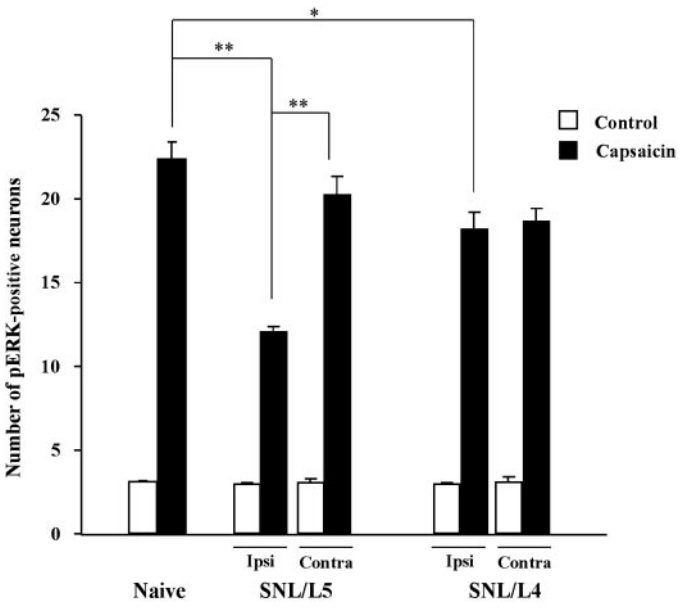

Fig. 4. Quantification of capsaicin-induced pERK-IR neurons in the superficial dorsal horn (laminae I–II) of spinal slices from control and injured rats (1 week after SNL). The L_5 or L_4 spinal slices were stimulated by capsaicin (3 μM, 5 min). *, $P < 0.05$; **, $P < 0.01$; ANOVA, $n = 5$. Notice that capsaicin-evoked pERK expression is decreased after nerve injury. Ipsi, ipsilateral side to nerve injury; Contra, contralateral side to nerve injury.

to be caused by a loss of TRPV1 receptors in primary afferents after nerve injury. pERK-IR neurons after SNL were still localized in the superficial (laminae I–II) dorsal horn (L_5) in response to capsaicin stimulation (Fig. 3). After SNL, capsaicin-induced pERK expression in the L_4 spinal slices was only slightly decreased ($P < 0.05$) compared with naive slices and pERK induction in the L_4 slices was significantly higher ($P < 0.01$) than that in the L_5 slices (Fig. 4).

Effects of Opioid and Cannabinoid Agonists on ERK Activation in the Spinal Cord of Nerve-Injured Rats. Although opioid receptor agonists DAMGO and morphine could inhibit capsaicin-evoked pERK induction in naive slices (Fig. 2), they were not able to suppress the pERK expression in the L_5 spinal slices after SNL (Figs. 3 and 5). In contrast, high dose of DAMGO (5 μM) could even potentiate capsaicin-induced ERK activation in the L_5 spinal cord (28% increase, $P < 0.01$; Fig. 3). On the other hand, cannabinoid CB1 agonist ACEA was still very effective in suppressing pERK induction by capsaicin (50 and 72% inhibition at 5 and 10 μM, respectively, $P < 0.01$; Fig. 5). The basal pERK expression in the L_5 slices (3.1 ± 0.1) was not significantly altered after short exposure (30 min) of DAMGO (2.7 ± 0.1, 1 μM), morphine (2.9 ± 0.1, 10 μM), or ACEA (2.9 ± 0.3, 10 μM). However, in the L_4 spinal slices of nerve-injured rats, capsaicin-induced ERK activation was significantly diminished by DAMGO (1 and 5 μM, $P < 0.01$), morphine (10 μM, $P < 0.01$), and ACEA (5 and 10 μM, $P < 0.01$) (Fig. 6).

Discussion

Opioids have been shown to induce ERK activation in several conditions. For example, acute morphine treatment (systemic for 30 min) is shown to induce ERK activation in the anterior cingulate and locus ceruleus (Eitan et al., 2003). Furthermore, modulation of ERK activation by acute morphine is brain region-specific; ERK activation is decreased in the nucleus accumbens and central amygdale (Eitan et al., 2003). Acute cannabinoid treatment was also shown to induce ERK activation in hippocampal neurons (Derkinderen et al., 2003). However, we did not see significant change in basal pERK expression following a short exposure of opioids and cannabinoids in the spinal cord, supporting the notion that ERK activation by opioids and cannabinoids is tissue-specific. However, it is likely that pERK might be induced in the spinal cord after chronic treatment of opioids and cannabinoids.

In the normal condition, we found that both opioids and cannabinoids can suppress C-fiber-induced ERK activation. Consistently, previous studies have shown that both opioids

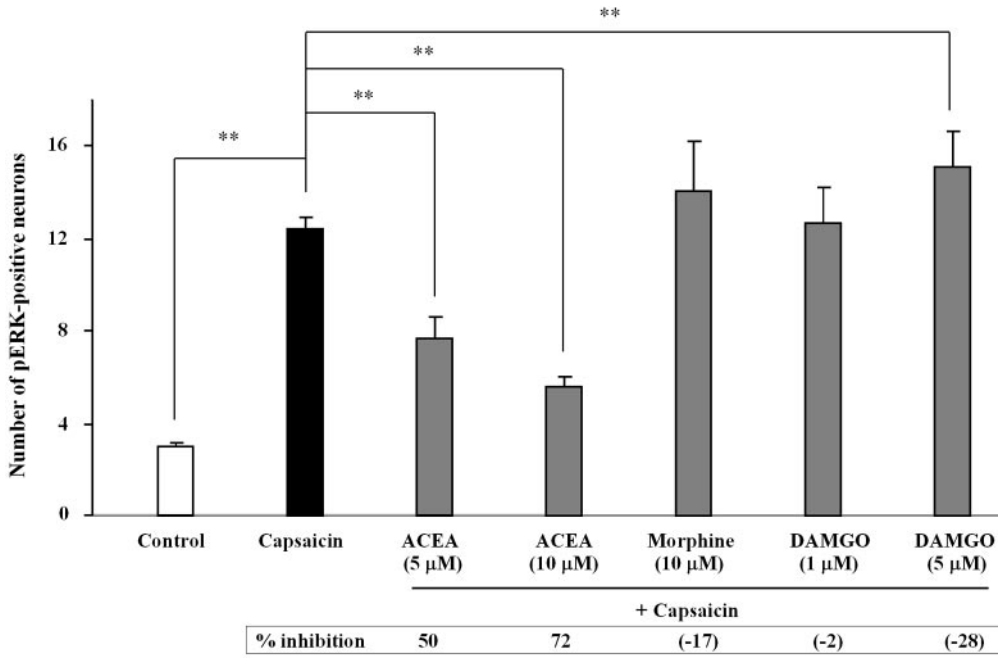

Fig. 5. Quantification of pERK-IR neurons in the superficial dorsal horn (laminae I–II) of L_5 spinal slices of nerve-injured rats (1 week after SNL). Capsaicin-induced increase in the number of pERK-IR neurons is suppressed by ACEA but not by DAMGO and morphine. **, $P < 0.01$, ANOVA, $n = 5$.

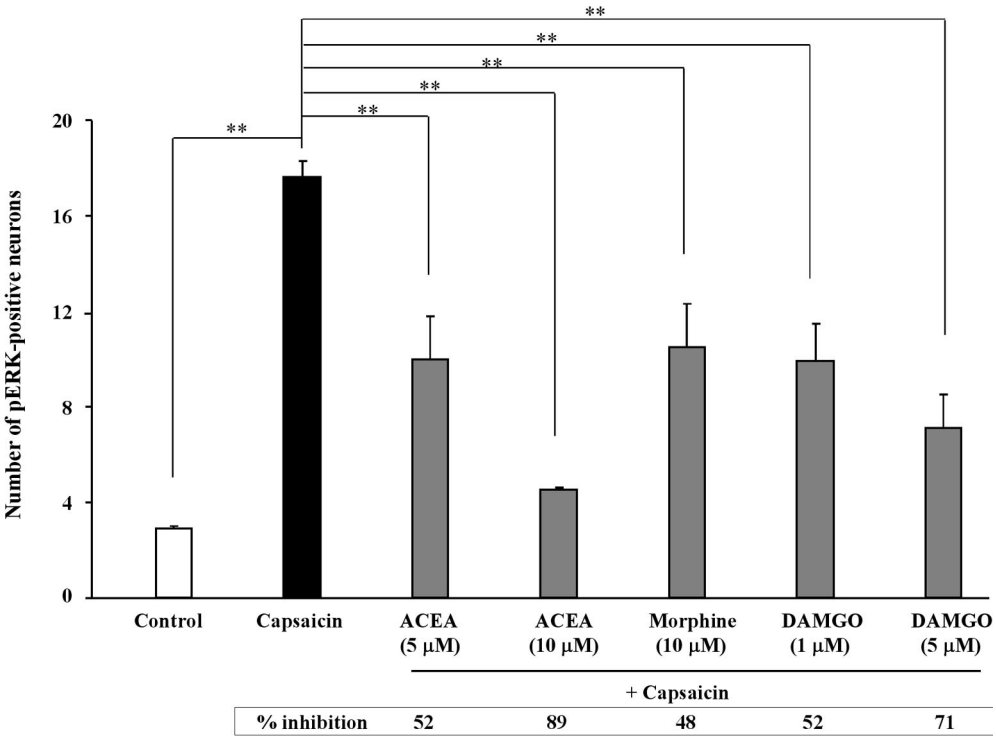

Fig. 6. Quantification of pERK-IR neurons in the superficial dorsal horn (laminae I–II) of spinal slices (L_4) of nerve-injured rats (1 week after SNL). Capsaicin-induced increase in the number of pERK-IR neurons is suppressed by ACEA, DAMGO, and morphine. **, $P < 0.01$, ANOVA, $n = 5$.

and cannabinoids can inhibit noxious stimulation-induced c-Fos expression in the spinal cord (Presley et al., 1990; Tsou et al., 1996). c-Fos expression is a downstream event of ERK activation, because ERK inhibition is shown to suppress c-Fos expression following noxious stimulation (Kawasaki et al., 2004). ERK activation is not only a marker for spinal neuron activation but also an important contributor to spinal neuron sensitization (Ji et al., 1999; Hu and Gereau, 2003; Kawasaki et al., 2004). Therefore, inactivation of spinal ERK could be a molecular mechanism underlying opioid- and cannabinoid-mediated analgesic effect. It remains to be investigated how opioids and cannabinoids suppress C-fiber stimulation-evoked pERK expression. It is likely that opioids and cannabinoids could regulate ERK phosphorylation via both presynaptic (e.g., reducing neurotransmitter release) and postsynaptic mechanisms (e.g., inhibiting the activity of adenylate cyclase). We have shown that protein kinase A is essential for capsaicin-induced pERK expression (Kawasaki et al., 2004). Therefore, opioids and cannabinoids could suppress pERK expression by inhibiting the activity of adenylate cyclase and subsequent activation of protein kinase A. Whereas in conditions of morphine tolerance, cAMP levels in dorsal horn neurons were increased, leading to opposite regulation of pERK.

Opioid receptors (μ, δ, and κ subtype) are normally present in small size (C- and Aδ-fiber) nociceptive dorsal root ganglion (DRG) neurons and their central terminals in the superficial dorsal horn. MOR is also expressed in lamina II dorsal horn neurons (Ji et al., 1995). Nerve injury induces a down-regulation of MOR both in DRG neurons and in the spinal cord after nerve injury (Porreca et al., 1998; Zhang et al., 1998). Recently, we have shown that down-regulation of MOR is restricted to the injured DRG and spinal segment (Kohno et al., 2005). Nerve injury also induces an up-regulation in DRG neurons of the peptide cholecystokinin (CCK) and its receptor CCK_B, which have been shown to antagonize opioid actions (Wiesenfeld-Hallin et al., 2002). The down-regulation of opioid receptors and up-regulation of the CCK system were thought to be responsible for the decreased efficacy of opioids after neuropathy (Xu et al., 1993; Wiesenfeld-Hallin et al., 2002). Moreover, the efficacy of opioid suppression of Aδ fiber-induced presynaptic and postsynaptic electrical responses in the injured spinal segment is also reduced (Kohno et al., 2005). A loss of MOR agonist activity after nerve injury may reflect decreased transcription, translation, and trafficking of the receptor to the membrane, as well as an uncoupling of the receptor from G proteins. However, Porreca et al. (1998) have shown that nerve injury only reduces the expression level of MOR in the injured spinal segment but does not change the density or affinity of MOR and morphine's potency in activating G proteins (Porreca et al., 1998). In contrast, peripheral inflammation increases MOR expression in DRG neurons, in support of increased analgesic sensitivity to opioids (Ji et al., 1995).

In agreement with a loss of MOR in the injured spinal segment, our results showed that DAMGO and morphine have lost their ability to inhibit C-fiber-induced ERK activation in the L_5 spinal cord after SNL, suggesting that MOR-mediated intracellular signaling is also impaired in the injured spinal cord. It has been shown that morphine tolerance (a neuronal adaptation to long-term morphine exposure or high-dose morphine) develops more rapidly after nerve injury. Opioid could even produce hyperalgesia after the tolerance (Mao et al., 1995; Ossipov et al., 2004). Interestingly, our data have shown that, after nerve injury, high dose of opioid can further potentiate C-fiber-induced ERK activation instead of inhibiting ERK activation. Therefore, opioid could both reduce and enhance pERK expression under different conditions, producing both antinociceptive and pronociceptive effects. ERK activation may underlie both antinocicep-

tive and pronociceptive effects of opioid depending on the doses and duration (acute versus chronic) of opioid treatment and animal conditions (naive versus nerve injured).

In contrast to a diminished opioid efficacy in the L_5 segment in response to C-fiber stimulation, CB1 agonist ACEA was fully capable of suppressing C-fiber-induced ERK activation after SNL. CB1 is strongly expressed in the superficial spinal cord, including primary afferent terminals and local neurons (Farquhar-Smith et al., 2000). Moreover, CB1 level is increased in the spinal cord after nerve injury (Lim et al., 2003). It remains to be investigated whether CB2 might also contribute to ERK activation in dorsal horn neurons. However, CB2 is typically expressed in the peripheral non-neural tissue and has been shown to contribute to the development of neuropathic pain via a peripheral mechanism (Ibrahim et al., 2003). CB2 activation produces antinociception by stimulating peripheral release of endogenous opioids (Ibrahim et al., 2003). Recent evidence indicates that CB2 receptor might be induced in spinal microglia after nerve injury (Zhang et al., 2003). Because the psychoactive effects of cannabinoids are mediated by CB1, development of CB2 agonists for pain relief could avoid devastating side effects of CB1 agonists. Recently, we found that pERK is also induced in spinal microglia at early stage (first several days) of nerve injury, which is important for the development of neuropathic pain (Zhuang et al., 2005). It is likely that spinal CB2 agonists may reduce neuropathic pain by suppressing MAPK (p38 and ERK) activation in spinal microglia (Jin et al., 2003; Ji and Strichartz, 2004). However, in spinal cord slices prepared from rats with 1-week nerve ligation, we did not see significant ERK activation in spinal microglia in the superficial spinal cord. This could be due to 1) a loss of pERK staining during slice preparation and 2) decline of microglial pERK induction after 1 week.

A great advantage to use the spinal nerve ligation model is that the injured and noninjured fibers are clearly separated in the different DRGs (L_5 versus L_4) and spinal segments (L_5 versus L_4) in this model. Spontaneous activity, which is believed to play an important role in the generation of neuropathic pain, develops in both the injured and the adjacent intact axons as well as in their somata. A loss of MOR activity on injured primary afferent central terminals and the second-order neurons they innervate may minimize the opioid reduction of spontaneous pain mediated by ectopic input from axotomized afferents. On the other hand, our data showed that DAMGO retains its potency to suppress C-fiber-induced pERK in the intact L_4 spinal segment after SNL. Thus, retention of MOR activity in nearby intact afferents will enable an opioid-mediated reduction of stimulus-evoked and spontaneous pain carried by intact nociceptor afferents. It is worthwhile to mention that, after SNL, pain signal from the tested hindpaw should be transmitted via intact fibers, because injured axons have lost their connections to the peripheral targets.

In summary, the efficacy of opioids in treating neuropathic pain is a highly debated issue. Recent animals and clinical studies indicate that the potency of opioid remains unchanged at least in some neuropathic pain conditions. However, molecular and cellular mechanisms of opioid actions are only partially known. We have shown that phosphorylation of the signaling molecule ERK could be a useful tool to study neuronal sensitivity to opioid treatment in both normal and nerve-injured conditions. Inactivation or activation of spinal ERK is likely to be a molecular mechanism of opioid-induced analgesia or hyperalgesia. Our results support a diminished efficacy of opioid in the injured spinal segment, in response to C-fiber-induced neuronal activation after spinal nerve ligation. Therefore, opioids may reduce sensitivity in those patients whose pain is generated mainly from injured nociceptor discharge. However, opioid may still be able to suppress neuropathic pain via acting on intact primary afferents or via supraspinal mechanisms. Because the efficacy of cannabinoid in suppressing C-fiber-induced pERK expression fully remains in the injured spinal segments after nerve ligation, our results support an undiminished potency of cannabinoid in attenuating neuropathic pain. Our data also suggest that there might be different regulatory mechanisms of opioids and cannabinoids for neuropathic pain.

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