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Morphine, Oxycodone, and Fentanyl Exhibit Different Analgesic Profiles in Mouse Pain Models†

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Abstract. Morphine, oxycodone, and fentanyl are clinically prescribed drugs for the management of severe pain. We investigated whether these opioids possess different efficacy profiles on several types of pain in mouse pain models. When the three opioids were tested in the femur bone cancer model, all of them significantly reversed guarding behavior, whereas the effects on limb-use abnormality and allodynia-like behavior differed among the opioids. Particularly, although oxycodone (5 – 20 mg/kg) and fentanyl (0.2 mg/kg) significantly reversed limb-use abnormality, not even a high dose of morphine (50 mg/kg) could reverse it. When the effects of these opioids were examined in a sciatic nerve ligation (SNL) model of neuropathic pain, oxycodone was the most effective, producing an antinociceptive effect without affecting the withdrawal threshold of sham-treated animals. When the effects of these opioids were examined with the tail-flick test using naive animals, oxycodone, morphine, and fentanyl exhibited antinociceptive effects on thermal nociception. These results show that the three opioids exhibit different efficacy outcomes in multiple pain models and that the efficacy profile of oxycodone does not overlap those of morphine and fentanyl.

Keywords: oxycodone, morphine, fentanyl, neuropathic pain-like state, bone cancer pain

Introduction

Morphine, oxycodone, and fentanyl are clinically prescribed opioids for the management of severe pain. These opioids possess strong antinociceptive effects on various types of pain related to abnormal physical conditions (1); however, certain types of pain are difficult to control with an opioid. For example, neuropathic pain, caused by nerve injury, does not respond effectively to opioids (2). As a result, tricyclic antidepressants (3) and/or serotonin/noradrenaline re-uptake inhibitors (4) are prescribed for this type of pain. Bone cancer pain is another example in which treatment with opioid alone is often insufficient (5 – 7). Although the doses of opioid may be gradually increased to obtain better pain relief, adverse effects such as drowsiness or respiratory depression become problematic, as those adverse effects significantly affect the patient's quality of life (8 – 10). To more effectively manage cancer pain, a combination of an opioid and a non-opioid analgesic

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such as an anticonvulsant, an antidepressant, or a local anesthetic has been preferred for a better clinical outcome (11, 12).

Among several opioids, oxycodone has recently been recommended for the treatment of cancer and non-cancer pain (13). Several clinical reports have shown that oxycodone effectively relieved pain in patients suffering from bone cancer pain or neuropathic pain induced by post-herpetic neuralgia (PHN) or diabetic neuropathy (DNP). For example, Bercovitch and Adunsky (14) reported that a high dose of oxycodone (e.g., 231 mg/day) could relieve bone cancer pain, and Watson et al. reported that controlled-release oxycodone was effective to manage pain induced by PHN (15) and DNP (16).

The antinociceptive effects of oxycodone, morphine, and fentanyl have been studied in several animal pain models. These opioids exhibited the significant antinociceptive effects, as measured by the tail-flick test, on pain caused by thermal stimuli (17). In the mouse sciatic nerve ligation (SNL) model, oxycodone has been shown to reverse the nociceptive pain caused by mechanical stimuli (18). Furthermore, in a mouse femur bone cancer (FBC) model, which showed similar pathological symptoms to human bone metastasis, morphine and fentanyl were reported to exhibit antinociceptive effects on several pain-related behaviors (19). Although those studies showed that these opioids were effective on several different types of pain, only a few studies have directly compared the pharmacological efficacy of the three opioids in animal pain models (17). For an appropriate opioid use, it is important to understand the pharmacological profile of each opioid in various types of pain.

In the present study, the pharmacological efficacies of morphine, oxycodone, and fentanyl were investigated in the FBC and the SNL models as well as in the tail-flick test. Our results showed that morphine, oxycodone, and fentanyl exhibited different efficacy profiles in some of the mouse pain models. Among the three opioids, oxycodone showed the most favorable analgesic effect in both the FBC and the SNL models.

Materials and Methods

Experimental animals

The experiments were performed using male C3H/HeN mice (CLEA Japan, Inc., Tokyo) and male ICR mice (Japan SLC, Inc., Shizuoka), weighing 18 – 23 and 20 – 25 g, respectively. The mice were housed in a vivarium with a 12-h alternating light-dark cycle and were given food and water ad libitum. All procedures were approved by the Animal Care and Use Committee of Shionogi Research Laboratories, Osaka, Japan.

Drug administration

Morphine hydrochloride (produced by Shionogi & Co., Ltd., Osaka), oxycodone hydrochloride (produced by Shionogi & Co., Ltd.), fentanyl citrate (Fentanyl injection; Daiichi-Sankyo Co., Ltd., Tokyo) were each dissolved in saline solution. The drug solutions were freshly prepared on each experimental day. Oxycodone, morphine, or fentanyl was administered subcutaneously 30 min before pain assessment.

The FBC model

For the FBC model, NCTC 2472 tumor cells (American Type Culture Collection, Manassas, VA, USA) were injected into the medullary cavity of the distal femur of C3H/HeN mice (20). The NCTC 2472 cells were maintained in Dulbecco's Modified Eagle's Medium (Invitrogen, Inc., Carlsbad, CA, USA), supplemented with 10% fetal bovine serum (Invitrogen, Inc.), 100 units/mL penicillin, and 100 μg/mL streptomycin (Invitrogen, Inc.); and they were cultured at 37 ± 0.2°C in a humidified atmosphere of 5% CO_2. The NCTC 2472 tumor cells were transfected with the luciferase gene in pUSEamp (Upstate, Lake Placid, NY, USA), using Lipofectamine 2000 (Invitrogen, Inc.). Transfected cells were selected by growth in medium containing 1 mg/mL G418 (Invitrogen, Inc.). Luciferase-expressing colonies were confirmed by measuring luciferase activity using an IVIS imaging system 200 (Xenogen Corp., Alameda, CA, USA) and were isolated by using cloning rings.

Tumor cells were injected following the protocol described previously by Honore et al. (20) with slight modification. In brief, mice were anesthetized with 0.2% xylazine (Selactar; Bayer Medical, Ltd., Tokyo) and 1% ketamine (Ketalar; Daiichi Sankyo Co., Ltd.), and a left knee arthrotomy was performed. Wild-type or luciferase-transfected tumor cells [1×10^5 cells in 5 μl of Hank's balanced salt solution (Invitrogen, Inc.)] were injected directly into the medullary cavity of the distal femur, and the drilled hole in the bone was closed with resin cement (ADFA; Shofu Inc., Kyoto). In the sham group, 5 μL of Hank's balanced salt solution was injected directly into the medullary cavity of the distal femur, and the drilled hole was repaired in the same manner.

Evaluations of tumor growth and bone destruction in the FBC model

Tumor-implanted mice were visualized by whole-body luciferase imaging with the IVIS imaging system 200 (Xenogen Corp.). Briefly, one milligram of potassium salt of D-luciferin dissolved in 0.1 ml phosphate-buffered saline (PBS, Invitrogen, Inc.) was injected intrave-

nously to mice using 27-gauge syringes. Then the mice were kept under anesthesia with isoflurane. Immediately starting after the luciferin injection, images were collected for 60 s. Relative tumor metastasis burden in mice was calculated with the Living Image software version 2.50 (Xenogen Corp.).

On 3, 7, 10, and 14 days after tumor implantation, the mice were anesthetized with diethylether and refluxed with 10% neutral buffered formalin. The femur bone was removed and fixed with 10% neutral buffered formalin for 2 days. The 3-μm–thick cross-sections of femur bone were stained by hematoxylin and eosin for histological analyses.

The extent of tumor-induced bone destruction (osteolysis) was monitored by X-ray radiography on 7, 14, and 21 days after tumor implantation. The mice were anesthetized with diethylether and refluxed with 10% neutral buffered formalin. Then the femur bone was removed and fixed with 10% neutral buffered formalin for 2 days. Removed femur bone was placed on wrapped films (Fuji Industrial X-ray Film FR; Fuji Photo Film, Kanagawa) and exposed to X-irradiation at 35 kV for 70 s using a Soft X-ray SOFRON Apparatus (Sofron, Tokyo).

Behavioral analysis in the FBC model

The behavioral analysis was preformed following the protocol described previously by Lugar et al. (21). The pain-related behaviors in the FBC model were evaluated before and after drug administration on 14 days after tumor implantation. The experimental and sham animals were evaluated for ongoing pain based on guarding behavior, for ambulatory pain based on limb-use abnormality, and for allodynia-like behavior based on the von Frey monofilament test. Guarding behavior and limb-use abnormality were assessed in the same animals, and allodynia-like pain was assessed in a separate set of animals.

The mice were placed in a clear plastic observation box and allowed to habituate for 15 min. Then the spontaneous guarding behavior was assessed during a 2-min observation period. The lifting time of the hind paw on the ipsilateral side during ambulation was measured as guarding behavior. Limb-use abnormality on the ipsilateral side during spontaneous ambulation was scored on a scale of 0 to 4: 0, normal use of limb; 1, slight limp; 2, clear limp; 3, partial non-use of limb; and 4, complete non-use of limb. Allodynia-like behavior was measured by the withdrawal threshold upon application of von Frey monofilament stimulation to the plantar surface of the hind paw (pressures: 0.008, 0.02, 0.04, 0.07, 0.16, 0.4, 0.6, and 1 g). The up-down method of von Frey monofilament test (22) was used in the present study. Briefly, the von Frey filaments were applied to the ipsilateral side of the hind paw for the maximum period of 4 s, and withdrawal response was observed. The 0.07-g stimulus was applied first. When withdrawal response to a given filament was observed, a one step thinner filament (a weaker stimulation) was applied. The same procedure was continued until the descending monofilament stimulation no longer induced the behavioral response. When no response was observed by the monofilament stimulation, a one step thicker monofilament (a stronger stimulation) was applied again to confirm the positive response. After that, no response was again confirmed by the one step thinner monofilament to complete the test, and the weakest stimulation that caused the positive response was taken as the threshold value. The mice showing the threshold change from 0.07 or 0.16 g (before tumor implantation) to 0.008 g (on the 14 days after tumor implantation) were used in the experiments.

Experiments using the SNL model

For the SNL model, ICR mice were anesthetized with 3% isoflurane, and a ligature was tied tightly with 8-0 silk suture around approximately 1/3 to 1/2 the diameter of the sciatic nerve on the left hind paw side (ipsilateral side), as described previously (23). In sham-operated mice, the nerve was exposed, but the nerve ligation was not performed. At 7 days after surgery, the drug efficacies were evaluated in these animals. The neuropathic pain-like state was assessed by measuring the withdrawal threshold using von Frey monofilament stimulation applied to the plantar surface of the hind paw (pressures: 0.008, 0.02, 0.04, 0.07, 0.16, 0.4, 0.6, and 1 g). The up-down method of the von Frey monofilament test was used as described above. The mice showing the threshold change from 0.07 or 0.16 g (before the surgery) to below 0.02 g (on the 7 days after the nerve ligation) were used in the experiments.

Assessment of anti-thermal nociception

The assessment of anti-thermal nociception was performed by the tail-flick test (Ugo Basile, Comerio, VA, Italy). The intensity of the heat stimulus was adjusted so that the intact animal flicked its tail within 2 – 4 s after stimulus application. The tail-flick response was measured before and after drug administration, and the cut-off time was set at 10 s to avoid injury to the tail.

Statistical analyses

All data are reported as values of the mean ± S.E.M. SAS software ver. 8 was used to perform the statistical analysis. One-way ANOVA was used to compare continuous data, including tail-flick latency and guarding

behavior, among the experimental groups. A Kruskall-Wallis test was used to compare discontinuous data, including neuropathic pain-like state, limb-use abnormality, and allodynia-like behavior, among the experimental groups. For multiple comparisons, Dunnett's test (for tail-flick latency and guarding behavior) or Steel's test (for neuropathic pain-like state, limb-use abnormality, and allodynia-like behavior) was used. For comparisons between two groups, Student's *t*-test (for guarding behavior) or the Wilcoxon signed-rank test (for limb-use abnormality and allodynia-like behavior) was used. A probability value (P) of <0.05 was considered to be statistically significant. The dose producing 50% of the effect (ED_{50}) was determined by inverse prediction based on the regression analysis.

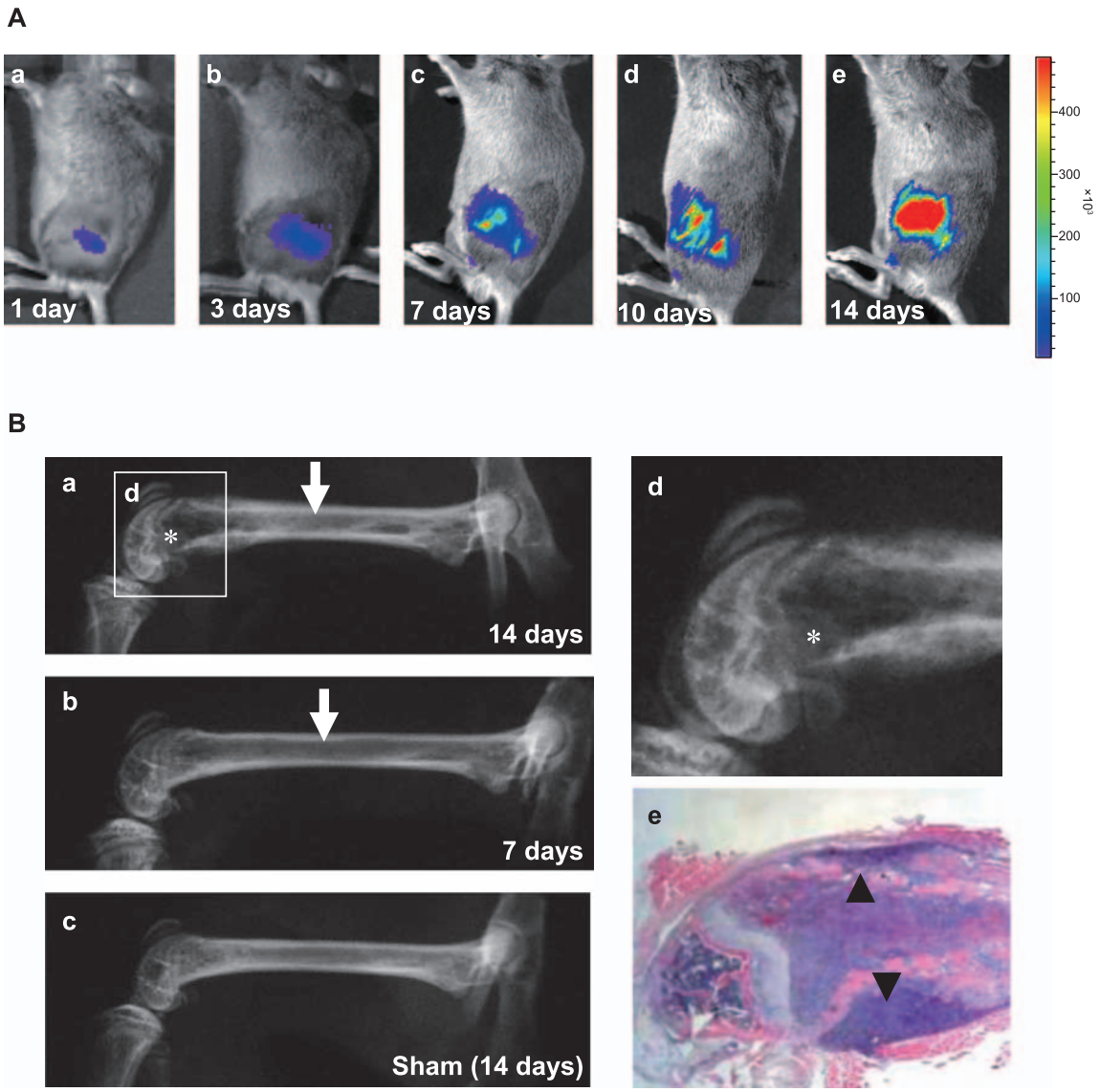

Fig. 1. Histological analysis of tumor growth. A: Luciferase gene–transfected NCTC2472 cells were implanted into the intramedulla of left femur bone (10^5 cells/5 μl). Luminescence was measured by IVIS®200 within 5 min after i.v. injection of luciferin (1 mg/ml) at 0.2 ml/mouse at 1 (a), 3 (b), 7 (c), 10 (d), and 14 (e) days after tumor implantation. The color, which indicates the intensity of photon emission, changes from blue to red as tumor cells grow. B: Radiographs show the left femur bone of the FBC model at 14 (a) and 7 (b) days in the tumor implanted–group and at 14 days in the sham-treated group (c), and the radiograph (d) expanded to show the distal part of the femur bone, which corresponds to the area surrounded by the square in photo Ba. The arrows and asterisk in the radiographs indicate the area of tumor implantation and bone destruction, respectively. The photomicrograph (e) shows the distal part of the femur bone, which is stained by hematoxilin and eosin. The arrow heads in the photomicrograph indicate the tumor cells that invade between the periosteum and the cortical bone.

Results

The histological analysis of tumor growth in the FBC model

The growth of the implanted tumor cells was investigated in the FBC model by monitoring the photon emission from the tumor cells stably expressing luciferase (Fig. 1A). On the first day after the tumor implantation, the photon emission was restricted within the implanted area with the low emission level (Fig. 1Aa). The progressive tumor growth was observed for 14 or more days after tumor implantation. The photon emission was not observed throughout the body even on 14 days after tumor implantation, suggesting that the tumor cells were retained within a relatively restricted area around the femur (Fig. 1A). Histological and X-ray analyses were applied to observe the anatomical changes in the femur bone, and we confirmed that the tumor cells progressively grew in the intramedulla and started invading the trabecular bone around 7 days after tumor implantation (Table 1). On 10 days after tumor implantation, the trabecular bone was filled with tumor cells (Table 1 and Fig. 1Be), which reached to the zone of ossification of the femur, followed by further invasion into the part between the periosteum and cortical bone on at 14 days after tumor implantation (see the black arrow heads in Fig. 1Be). The X-ray radiographs indicated that bone destruction occurred in the distal part of the femur bone by 14 days after tumor implantation (see the asterisks in Fig. 1: Ba and Bd). The radiographs and photomicrograph observations confirmed that there was invasion of the tumor cells at the area where bone destruction was observed. No significant change in the bone histology was observed in the sham-treated group on 14 days after the surgery (Fig. 1Bc).

Table 1. Histological analysis of tumor growth in the femur bone

	Tumor cells in femur bone	
	Extent	Observed area
3 days	±	Intramedulla
7 days	±, +, ++, +++	Intramedulla
10 days	+++	Intramedulla and trabecular bone
14 days	+++	Intramedulla Trabecular bone Between priosteum and cortical bone

The symbols in the table indicate the extent of tumor cell invasion as follows: (±) less than 10%, (+) 10% – 30%, (++) 30% – 60%, and (+++) over 60%.

The correlation between the tumor growth and pain-related behaviors in the FBC model

To evaluate the tumor growth level in the FBC model, the photon intensity was measured from the images captured by the IVIS. The levels of the emitted photon

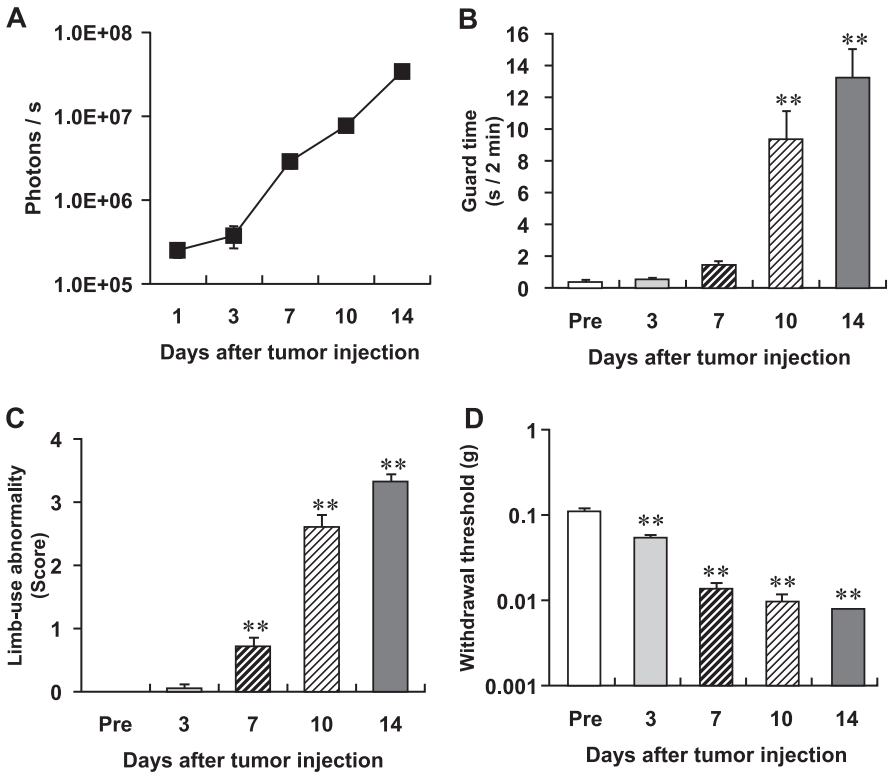

Fig. 2. The correlation between the tumor growth and the observed pain-related behaviors. The photons of luminescence captured in the IVIS imaging system were calculated by the Living Image Software on days 1, 3, 7, 10, and 14 after tumor implantation. The data represents the mean ± S.E.M. (n = 18) (A). Guarding (B), limb-use abnormality (C), and allodynia-like behavior (D) were measured at pre-implantation and on days 3, 7, 10, and 14 after tumor implantation. Each column and vertical bar show the mean ± S.E.M. of 18 measurements. $^{**}P<0.01$, compared with the pre-implantation (Pre) group (Dunnett's test). Modified from Ref. 37 (proceeding for The Fourth Asia Pacific Symposium on Pain Control, Kuala Lumpur, November 2 – 4, 2007) with permission from S. Karger AG, Basel.

intensity gradually increased after the tumor cell implantation, and the level at 3 days after tumor implantation was approximately1.5-fold of the level on day 1, 11-fold at day 7, 31-fold at day 10, and 135-fold at 14 days after tumor implantation (Fig. 2A). The previous studies showed that several pain-related behaviors were observed in the FBC model. Guarding behavior is thought to indicate ongoing pain, limb-use abnormality is thought to represent ambulatory pain, and an allodynia-like behavior is thought to represent touch-evoked pain in this model (21). We, therefore, investigated whether these behaviors were correlated with tumor growth. The guard times were significantly prolonged at 10 and 14 days after tumor implantation compared with the values at pre-implantation (Fig. 2B). Similarly, animals also started to exhibit abnormal limb-use at 7 days after tumor implantation, and such abnormal behavior was more prominent in the later days (Fig. 2C). Allodynia was evaluated by measuring the paw withdrawal threshold in response to probing with von Frey monofilaments, and significant threshold drops were observed after the 3rd day post tumor implantation (Fig. 2D). These results showed that those pain-related behaviors were correlatively observed with tumor growth in this model.

Effects of oxycodone, morphine, and fentanyl in the FBC model

We tested the effects of oxycodone, morphine, and fentanyl in the FBC model. The effects of each opioid were assessed by observing three pain-related behaviors: guarding behavior, limb-use abnormality, and allodynia-like behavior. Figure 3 shows that all three opioids similarly reduced the guarding time in the FBC model group without affecting the sham-treated group. In contrast, the antinociceptive effects on ambulatory pain differed among the opioids (Fig. 4). Within the range of doses that did not affect the sham-treated group, only oxycodone at 5 mg/kg exhibited a significant analgesic effect (Fig. 4). Although fentanyl at 0.2 mg/kg significantly improved the limb-use abnormality score, this dose of fentanyl also affected the sham-treated group. Morphine did not improve the limb-use abnormality score, even at the highest dose tested (50 mg/kg, s.c.) (Fig. 4). The effects of the opioids on allodynia-like behavior were measured using the von Frey monofilament test. Oxycodone (5 – 20 mg/kg, s.c.), morphine (50 mg/kg, s.c.), and fentanyl (0.075 – 0.2 mg/kg, s.c.) significantly reversed the decrease of the paw withdrawal threshold, indicating that all three opioids effectively reversed allodynia-like behavior (Fig. 5). However, the effective doses of morphine (50 mg/kg, s.c.) and fentanyl (0.1 and 0.2 mg/kg, s.c.) were close to or at the doses that affected the paw withdrawal threshold in the sham-treated group, while oxycodone reversed the allodynia-like behavior without affecting the sham group (Fig. 5).

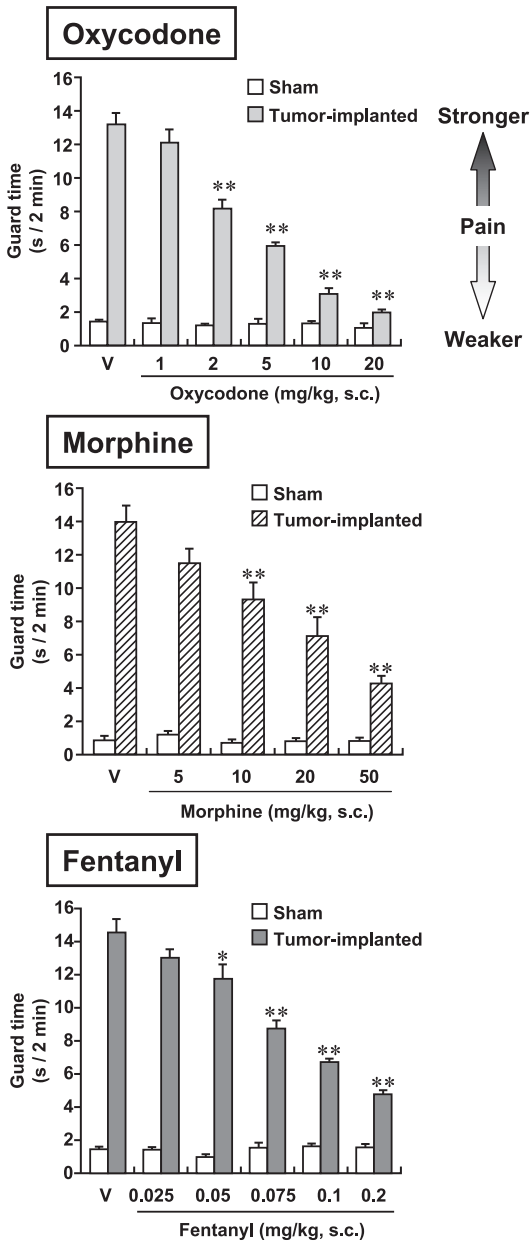

Fig. 3. The effects of oxycodone, morphine, and fentanyl on guarding behavior. The analgesic effects of oxycodone, morphine, and fentanyl on on-going pain in FBC model mice were evaluated based on guarding behavior. FBC model mice were used at 14 days after tumor implantation, and each opioid was administered subcutaneously 30 min before the measurement. Open and filled columns indicate the sham-treated and tumor-implanted groups, respectively. The columns and vertical bars show the means ± S.E.M. (n = 6 – 8). **P*<0.05, ***P*<0.01, compared with vehicle (V) in the tumor-implanted group (one-way ANOVA and Dunnett's test).

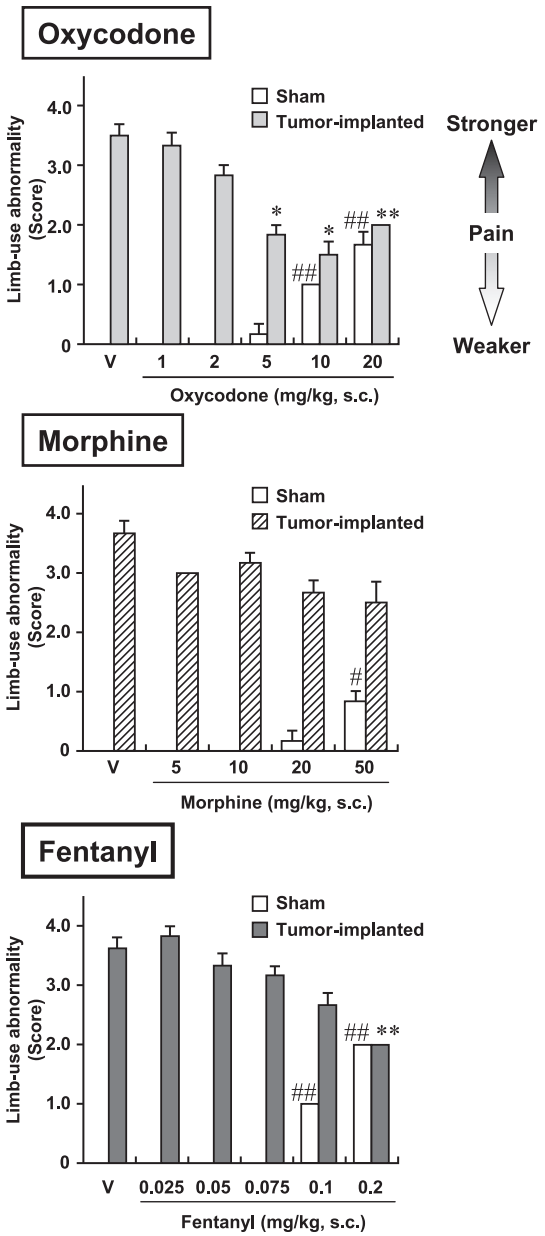

Fig. 4. The effects of oxycodone, morphine, and fentanyl on limb-use abnormality. The analgesic effects of oxycodone, morphine, and fentanyl on ambulatory pain in FBC model mice were evaluated based on limb-use abnormalities. FBC model mice were used at 14 days after tumor implantation, and each opioid was administered subcutaneously 30 min before measuring the limb-use abnormality score. Open and filled columns indicate the sham-treated and tumor-implanted groups, respectively. The columns and vertical bars show the means ± S.E.M (n = 6 – 8). **P*<0.05, ***P*<0.01, compared with vehicle (V) in the tumor-implanted group (Kruskall-Wallis test and Steel's test). #*P*<0.05, ##*P*<0.01, compared with vehicle (V) in the sham-treated group (Kruskall-Wallis test and Steel's test).

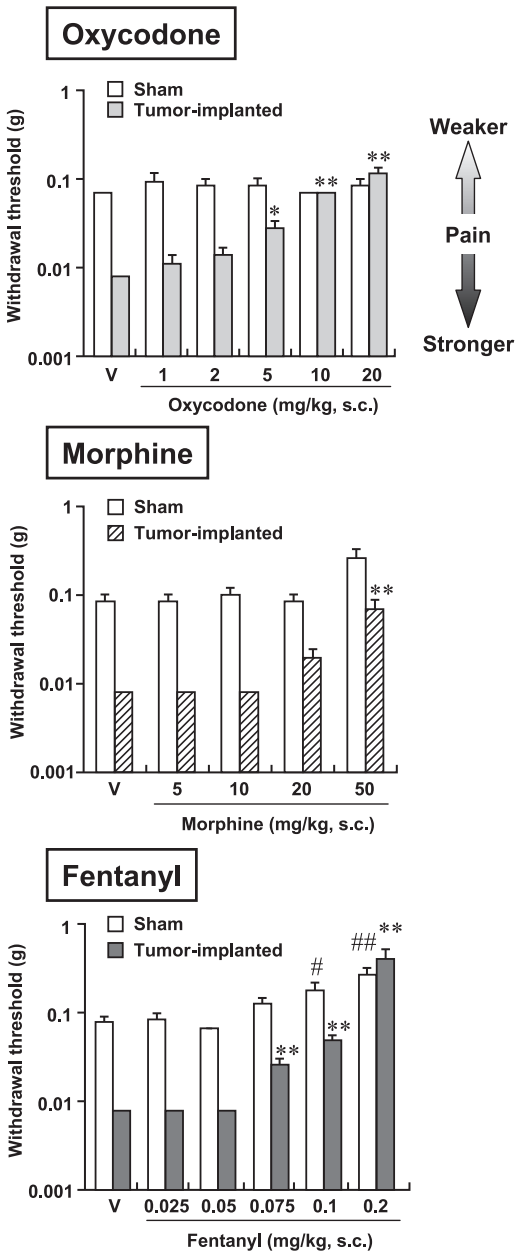

Fig. 5. The effects of oxycodone, morphine, and fentanyl on allodynia-like behavior. The effects of oxycodone, morphine, and fentanyl on allodynia-like behavior in FBC model mice were evaluated. FBC model mice were used 14 days after tumor implantation, and each opioid was administered subcutaneously 30 min before the measuring the withdrawal threshold in the von Frey monofilament test. Open and filled columns indicate sham-treated and tumor-implanted groups, respectively. The columns and vertical bars show the means ± S.E.M. (n = 6 – 8). **P*<0.05, ***P*<0.01, compared with vehicle (V) in the tumor-implanted group (Kruskall-Wallis test and Steel's test). #*P*<0.05, ##*P*<0.01, compared with vehicle (V) in the sham-treated group (Kruskall-Wallis test and Steel's test).

Effects of oxycodone, morphine, and fentanyl on a neuropathic pain-like state in SNL model mice

To evaluate the antinociceptive effects of oxycodone, morphine, and fentanyl on a neuropathic pain-like state, the withdrawal threshold to stimulation with von Frey monofilaments was measured in the hind paw of SNL

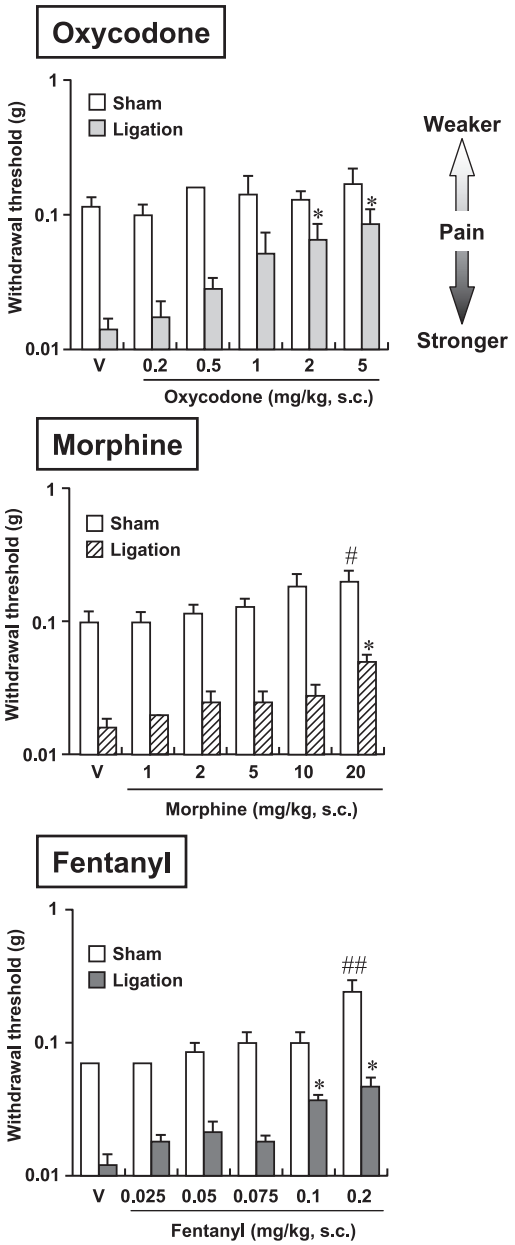

Fig. 6. The effects of oxycodone, morphine, and fentanyl on the neuropathic pain-like state. The antinociceptive effects of oxycodone, morphine, and fentanyl on a neuropathic pain-like state in sciatic nerve ligation (SNL) model mice were evaluated. Seven days after nerve ligation, each opioid was administered subcutaneously 30 min before measuring the withdrawal threshold to stimulation with von Frey monofilaments. Open and filled columns indicate the sham-treated and SNL groups, respectively. The columns and vertical bars show the means ± S.E.M. (n = 8). **P*<0.05, compared with vehicle (V) in the SNL group (Kruskall-Wallis test and Steel's test). #*P*<0.05, ##*P*<0.01, compared with vehicle (V) in the sham-operated group (Kruskall-Wallis test and Steel's test).

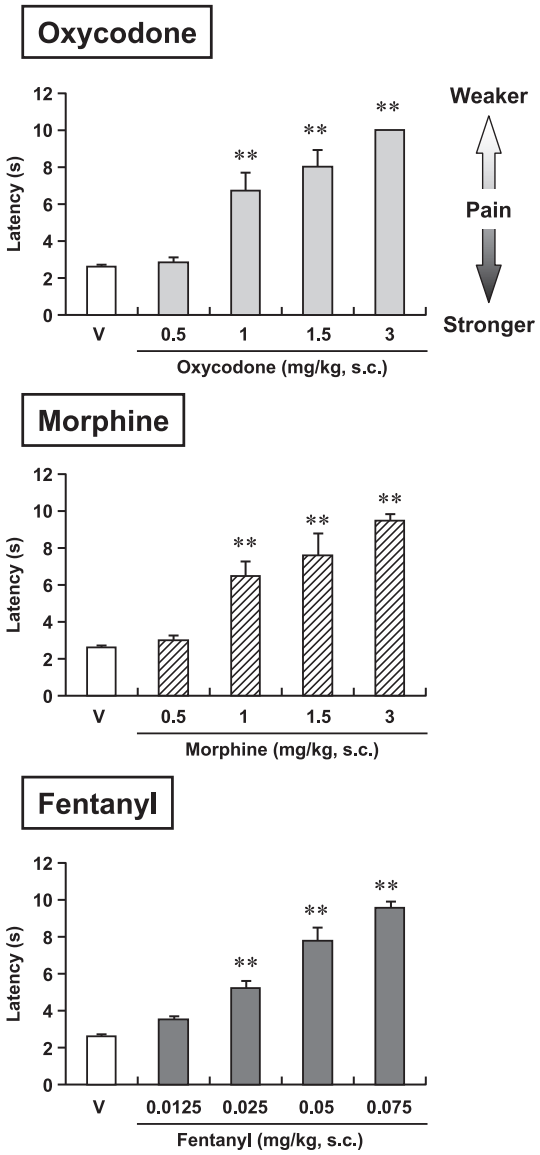

Fig. 7. The effects of oxycodone, morphine, and fentanyl on thermal nociception. The antinociceptive effects of oxycodone, morphine, and fentanyl on thermal nociception in intact ICR mice were evaluated using the tail-flick test. Each opioid was administered subcutaneously 30 min before the measurement. The cut-off time was set at 10 s in the test to avoid injury to the tail. The columns and vertical bars show the means ± S.E.M. (n = 6). ***P*<0.01, compared with the vehicle (V) group (one-way ANOVA and Dunnett's test).

model mice. Oxycodone (2 and 5 mg/kg, s.c.) significantly reversed the decreased withdrawal threshold induced by physical ligation of the sciatic nerve. The strongest analgesic effect (approximately 80% of reversal) occurred with the 5-mg/kg dose, which did not affect the paw withdrawal threshold in the sham-treated group (Fig. 6). Although morphine (20 mg/kg, s.c.) and fentanyl (0.1 and 0.2 mg/kg, s.c.) also reversed the decreased withdrawal threshold in the experimental group, the high doses required were close to or at the doses that significantly affected the withdrawal threshold in the sham-treated group (Fig. 6). These results suggest

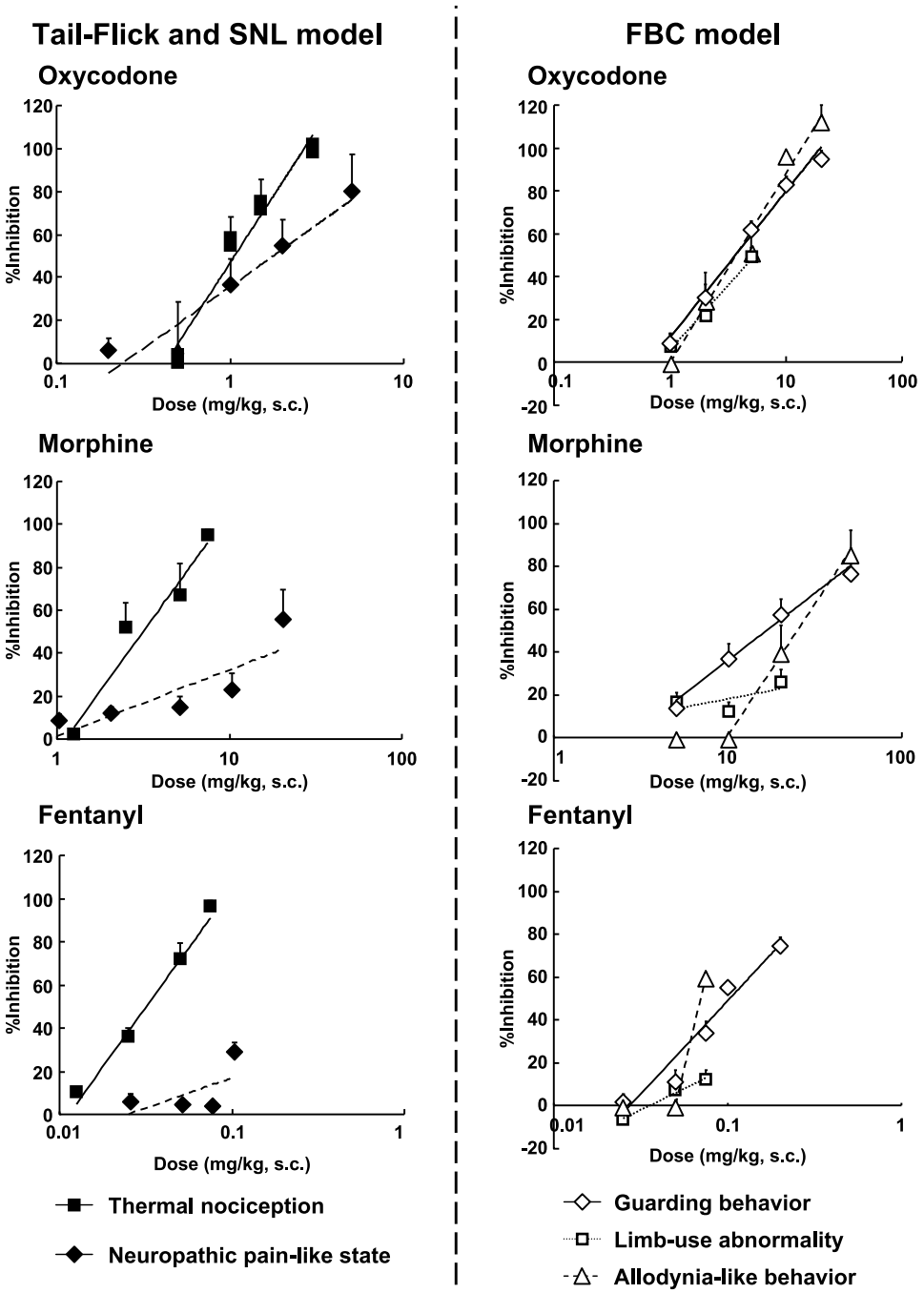

Fig. 8. The linear correlation between dose and percentage inhibition in each opioid obtained from the different pain models. Only the doses that did not affect the sham-treated group were included. Solid and broken lines show the linear correlations between dose and percentage inhibition for oxycodone, morphine, and fentanyl. The left side of the figure indicates the regression lines to thermal nociception in the tail-flick test (filled square) and neuropathic pain-like state in the SNL model (filled diamond). The right side indicates the regression lines to guarding behavior (open diamond), limb-use abnormality (open square), and allodynia-like behavior (open triangle) in the FBC model. The points and vertical bars show the means ± S.E.M. (n = 6 – 8). Right panels: Modified from Ref. 37 (proceeding for The Fourth Asia Pacific Symposium on Pain Control, Kuala Lumpur, November 2 – 4, 2007) with permission from S. Karger AG, Basel.

that among the three opioids, oxycodone has the most favorable pharmacological profile for the treatment of the neuropathic pain–like state in this model.

Effects of oxycodone, morphine, and fentanyl on thermal nociception in mice

To evaluate the antinociceptive effects of oxycodone, morphine, and fentanyl on thermal nociception, the tail-

Table 2. The ED_{50} values of oxycodone, morphine, and fentanyl for thermal nociception, neuropathic pain-like state, guarding behavior, limb-use abnormality, and allodynia-like behavior

	ED_{50} (mg/kg, s.c.) (95% Confidence limits)		
	Oxycodone	Morphine	Fentanyl
Thermal nociception			
ICR mice	0.91 (0.52 – 1.59)	3.00 (1.66 – 5.42)	0.031 (0.020 – 0.048)
Neuropathic-like state (SNL model)			
	1.8 (1.00 – 4.01)	>10	>0.1
Bone cancer pain (FBC model)			
Guarding behavior	5.96 (4.60 – 7.22)	23.6 (18.4 – 29.3)	0.122 (0.113 – 0.134)
Limb-use abnormality	5.04 (4.23 – 6.52)	>20	>0.1
Allodynia-like behavior	6.13 (4.22 – 7.86)	30.6 (24.5 – 37.9)	0.071 (0.070 – 0.071)

The ED_{50} values of oxycodone, morphine, and fentanyl for ongoing, ambulatory, and neuropathic pains were calculated from the regression equations of the regression lines (Fig. 8).

flick latency was measured in ICR mice. Oxycodone (1 – 3 mg/kg, s.c.), morphine (2.5 – 7.5 mg/kg, s.c.), and fentanyl (0.025 – 0.075 mg/kg, s.c.) significantly increased the tail-flick latency in a dose-dependent manner (Fig. 7). To test whether the relative efficacies of the opioids are affected by the genetic background of the model mice, the same experiment was repeated in C3H/HeN mice, which were used to develop the FBC model. Virtually no differences in the effective doses or relative efficacies of the three opioids were observed between the two mouse strains (data not shown). These results show that oxycodone, morphine, and fentanyl are all effective in relieving thermal nociception.

Comparison of the ED_{50} values of oxycodone, morphine, and fentanyl for relieving several types of pain

To compare the equivalent dose-ratios of oxycodone, morphine, and fentanyl, the regression lines of the dose–response relationships for the antinociceptive effects of the three opioids in the mouse pain models were compared. In drawing the regression lines, we excluded the doses that affected behavior in the sham-treated group (Fig. 8) because the behavioral measurements at such doses may reflect not only the antinociceptive effect but also an effect on general behavior. Table 2 shows the ED_{50} values calculated from the regression equations. The ED_{50} values of oxycodone, morphine, and fentanyl for anti-thermal nociception were 0.91, 3.00, and 0.031 mg/kg, respectively. The equivalent dose-ratio is consistent with the previous results reported by others (18). In the SNL model, the ED_{50} value of oxycodone was approximately 2-fold that for anti-thermal nociception. However, the ED_{50} values of morphine and fentanyl could not be calculated in this model because these two opioids did not exhibit at least a 50% reversal of pain-related effects without affecting the behavior of the sham-treated group. In the FBC model, the ED_{50} value of oxycodone was similar among the three different pain behaviors and was approximately 6-fold that for anti-thermal nociception. The ED_{50} values of fentanyl determined by guarding and allodynia-like behaviors were approximately 2- to 4-fold the ED_{50} value of fentanyl for anti-thermal nociception. The ED_{50} values of morphine based on guarding and allodynia-like behaviors were 8- to 10-fold the ED_{50} value of morphine for anti-thermal nociception. However, the ED_{50} values of fentanyl and morphine could not be calculated based on the limb-use abnormality assessment because an adverse effect was observed in the sham group before reaching 50% pain reversal. These results demonstrate that the three opioids have different analgesic efficacies depending on the pain model examined. Among the three opioids, oxycodone appeared to exhibit a preferable pharmacological profile compared with the other two opioids, especially in the SNL and the FBC models.

Discussion

In the present study, the efficacy profiles of oxycodone, morphine, and fentanyl were examined in three mouse pain models. These μ-opioid receptor agonists were found to exhibit different antinociceptive effects in

the FBC and the SNL models. Oxycodone reversed all types of pain examined in the three mouse pain models, whereas morphine and fentanyl were less effective on the ambulatory pain in the FBC model and the neuropathic pain-like state in the SNL model. Thus, oxycodone appears to have distinct analgesic effects compared with the other two opioids.

We employed the FBC model to examine opioid efficacy on bone cancer–related pain in this study. The FBC model was useful as a bone cancer pain model because pain and the pathological changes including bone destruction and nerve compression (21, 24 – 26) were observed within a relatively short period of time (within a few weeks) after implantation of the tumor cells (Fig. 1) (21, 24 – 27), and those were similar to some of the symptoms observed in bone cancer patients. For example, bone cancer patients typically report numbness in the beginning, but the pain becomes severe as the disease progresses, eventually resulting in bone destruction (28, 29). In the FBC model, allodynia-like behavior began within a week after tumor implantation when bone destruction had not yet been observed (Figs. 1 and 2). In the late phase (e.g., within 7 – 14 days), guarding behavior and limb-use abnormality were observed, accompanied by bone destruction, suggesting that the FBC model mimics some of the clinical features observed in human bone cancer pain. In this model, oxycodone exhibited antinociceptive effects on all three types of pain: ongoing, ambulatory, and allodynia-like. On the other hand, neither morphine nor fentanyl exhibited antinociceptive effects on limb-use abnormality without affecting the sham-treated groups. Thus, oxycodone has a preferable overall efficacy profile in this bone cancer pain model.

Since the behavioral changes such as guarding behavior and limb-use abnormality were used to evaluate the efficacy of the opioids, it is possible that the opioid-induced hyperlocomotion might influence the behavioral evaluations in the FBC model. In fact, we found that subcutaneous administration of all three opioids (morphine at 20 mg/kg, oxycodone at 10 mg/kg, fentanyl at 0.1 mg/kg) increased spontaneous activity approximately 2-fold (data not shown). However, the opioid treatments in this study did not affect the functional aspect of the behaviors because no abnormality was observed in the motor function after these opioid treatments even at the highest doses used in the Rota-rod test (morphine at 50 mg/kg, s.c.; oxycodone at 20 mg /kg, s.c.; fentanyl at 0.2 mg/kg, s.c.) (data not shown). Nevertheless the effect of each opioid on the guarding behavior and the limb-use abnormality differed, indicating that the distinctive pharmacological profiles, rather than the general opioid-induced hyperlocomotion, account for the different efficacy in the FBC models.

Neuropathic pain is another clinical situation that does not often respond effectively to opioids. Recently, several clinical reports have shown that oxycodone was effective in controlling neuropathic pain related to DNP and PHN (15, 16). In the present study, we tested the efficacy of the opioids in the animal pain model showing neuropathic pain-like behavior. Among the three opioids, oxycodone exhibited greater antinociceptive effects on allodynia-like behavior in the FBC model and on the neuropathic pain-like state in the SNL model within a dose range that did not affect the sham group. These results suggest that oxycodone may possess distinct pharmacological profiles in the treatment for some types of neuropathic pain.

In contrast to the efficacy in the FBC and the SNL models, all three opioids displayed antinociceptive effects on thermal nociception in the tail-flick test, which has been commonly used to evaluate the efficacy of many drugs including opioids. The equivalent dose-ratio calculated from the ED_{50} values of oxycodone, morphine, and fentanyl was approximately 1:3:0.03, which is similar to the previously reported ratio (18). On the other hand, the equivalent dose-ratio was changed when these opioids were tested in other types of pain, showing that the efficacy profiles of those opioids differ depending on the types of pain to control. It is important to understand the efficacy profile of each opioid for appropriate opioid use.

In the present study, we used relatively high doses of the opioids. Although it is difficult to speculate whether the doses used in the present study are clinically relevant, the plasma concentration after the subcutaneous injection of morphine at 5 mg/kg and oxycodone at 2 mg/kg in mice were similar to those after oral administration of 300 mg/day of morphine and 120 mg/day of oxycodone in humans, respectively. This may suggest that the opioid doses used in our studies were not far different from the clinically used dose-ranges to manage cancer-related severe pain (14, 30). However, this kind of analysis may not be appropriate, and special care is needed to compare our animal study to the clinical setting. In the meanwhile, it is noteworthy that some recent papers showed that the clinical doses of oxycodone were effective for relieving pain in patients suffering from bone metastasis or neural injury (15, 16, 31).

One other interpretation of our results in the FBC model is that the opioid treatments might have rapidly inhibited tumor growth, so that pain intensity was alleviated as a result of reduced tumor size in the bone rather than an antinociceptive effect. Therefore, the effect of each opioid on the size of the implanted tumor in the FBC model mice was tested by using a bio-

luminescent imaging system. None of the opioid treatments inhibited the tumor size at 30 min or 24 h after drug administration (data not shown), showing that a change in tumor size did not contribute to the observed analgesic effect of oxycodone, morphine, or fentanyl.

Nielsen et al. (32) previously reported that the antinociceptive effect of oxycodone is mediated by the κ-opioid receptor. One could assume, therefore, that the difference in the efficacy profiles among the opioids may originate from a difference in the activated receptors and that the κ-opioid receptor as well as the μ-opioid receptor may mediate the effects of oxycodone, resulting in better drug efficacy. Our preliminary data, however, suggested that the antinociceptive effects of all three opioids in the FBC model were completely antagonized by a μ-opioid receptor antagonist, β-FNA, and not by a κ-opioid receptor antagonist, nor-BNI (K. Minami et al., in preparation). Therefore, the μ-opioid receptors appeared to mediate the analgesic effects of all three opioids.

Currently no data is available to explain the observed difference in the pharmacological profiles among these three opioids. There are, however, several possible hypotheses. For example, it has been reported that several receptors are known to couple to multiple effecters to initiate downstream signals and that different ligands can promote distinct relative efficacies in the downstream signals, resulting in a ligand-dependent efficacy profile (33). Another possibility is that different types of the μ-opioid receptor splice variants are responsible for different efficacy of each opioid. Several μ-opioid receptor splice variants have been identified (34), and it is possible that each splice variant may utilize a different downstream signaling pathway or are expressed in different anatomical regions to exhibit a distinctive pharmacological profile. Moreover, heterodimerization of the μ-opioid receptor and other receptors is another possible mechanism for the different opioid efficacy since the intracellular signals including a coupled G-protein can be affected by receptor dimerization (35, 36). Additional experiments are required to verify these hypotheses.

In conclusion, the present study showed that oxycodone produced the most distinguished antinociceptive effects on the FBC and SNL models. The analgesic effects of all three opioids are suggested to be mediated via μ-opioid receptors. It is of great interest to investigate the underlying mechanisms of the different efficacies among these μ-opioid agonists.

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