Mashiningan Improves Opioid-Induced Constipation in Rats by Activating Cystic Fibrosis Transmembrane Conductance Regulator Chloride Channel

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ABSTRACT

Opioid receptor stimulants are analgesics used in patients with and without cancer; however, they often cause constipation, resulting in poor adherence and deterioration of the quality of life. Hence, suitable treatments for constipation are required. In this study, we investigated the pharmacological mechanisms of action of mashiningan (MNG), a Kampo medicine used to treat constipation, and evaluated the effect of MNG on opioid-induced constipation in rats. MNG (100 or 300 mg/kg) was orally administered to normal or NhBE rats. MNG prevented these effects and increased the proportion of soft feces. MNG increased the electronic chloride current, and this effect was inhibited by the CFTRinh-172 in the CFTR assay. Furthermore, MNG increased small intestinal fluid secretion, and this effect was abolished by coadministration with the CFTRinh-172. MNG improved opioid-induced constipation in rats, and this improvement may have been mediated by increasing intestinal fluid secretion via CFTR chloride channel activation. Therefore, MNG is expected as a medicine of the treatment of constipation in patients taking opioids.

Introduction

Constipation is a common disorder of the digestive tract observed in 12–19% of people (Gras-Miralles and Cremonini, 2013), especially in the elderly aged 65 years or older in Asia (Kurniawan and Simadibrata, 2011). The number of patients with cancer is currently increasing gradually, and these patients need pain relief at all stages of their disease. The mainstay of the management of cancer pain is opioid-based pharmacotherapy (Canadian Agency for Drugs and Technologies in Health, 2014). However, the use of opioids in the treatment of chronic pain in patients with and without cancer causes bowel disorders as an adverse effect. The most frequent of these disorders is constipation, which often results in the discontinuation of opioid therapy (McNicol et al., 2003; Gywali et al., 2015; Sani and Mahan, 2015; Nelson and Camilleri, 2016). Therefore, opioid-induced constipation compromises pain management.

For severe constipation, proactive medical treatment is required to improve the quality of life of patients and increase their satisfaction with therapy (LoCasale et al., 2016). Currently, various medications are available for treating constipation, such as laxatives and enemas, depending on the symptom and type (Prichard et al., 2016). Additionally, chloride channel activators have drawn attention as new medicines that are associated with intestinal fluid secretion. It has been reported that phenylquinoxalinone, a cystic fibrosis transmembrane conductance regulator (CFTR) specific inhibitor (CFTRinh-172). The effects of MNG on the CFTR and type-2 chloride channel were determined using patch-clamp or short-circuit current experiments, respectively. MNG increased the fecal weight and proportion of soft feces in normal rats. CPH-induced constipation in rats decreased fecal counts and weight, whereas MNG prevented these effects and increased the proportion of soft feces. MNG increased the electronic chloride current, and this effect was inhibited by the CFTRinh-172 in the CFTR assay. Furthermore, MNG increased small intestinal fluid secretion, and this effect was abolished by coadministration with the CFTRinh-172. MNG improved opioid-induced constipation in rats, and this improvement may have been mediated by increasing intestinal fluid secretion via CFTR chloride channel activation. Therefore, MNG is expected as a medicine of the treatment of constipation in patients taking opioids.

ABBREVIATIONS: CFTR, cystic fibrosis transmembrane conductance regulator; CFTRinh-172, CFTR-specific inhibitor; CIC-2, type-2 chloride channel; CPH, codeine phosphate; DW, distilled water; GC-C, guanylate cyclase-C; IP, intraperitoneal; MNG, mashiningan; NhBE, normal human bronchial epithelial cell; OP, opioid μ; PBS, phosphate-buffered saline containing 0.3% dimethyl sulfoxide; PO, per os.
such as habit formation, abdominal pain, and nausea (Izzy et al., 2016).

Mashiningan (MNG), a Kampo medicine composed of six crude drugs, is widely prescribed to patients with abdominal sensations such as lumpy or hard stools and symptoms of frailty after illness or associated with aging in Japan and other Asian countries (Iizuka and Hamamoto, 2015; Nakae et al., 2016). The efficacy and safety of MNG in alleviating functional constipation symptoms have also been reported in randomized double-blind, placebo-controlled studies in China (Cheng et al., 2011; Zhong et al., 2013). However, its precise mechanism of action has not been fully understood. Therefore, in the present study, we investigated the pharmacological mechanisms of action of MNG and evaluated the effect of MNG on opioid-induced constipation in rats.

Materials and Methods

Animals

Six-week-old male Sprague–Dawley rats (weight, 160–210 g) were purchased from Japan Charles River (Kanagawa, Japan). All the animals were housed in stainless steel cages in a room with controlled ambient temperature (23 ± 3°C), humidity (50 ± 20%), and lighting (12-hour light:dark cycle) conditions. The animals were provided water and a standard laboratory animal diet (MF; Oriental Yeast, Tokyo, Japan) ad libitum. Experiments were performed using free-fed rats, except where otherwise mentioned. All experimental procedures were performed according to the Guidelines for the Care and Use of Laboratory Animals and approved by the Laboratory Animal Committee (Permits 15-021, 15-036, 16-044, and 16-053) of Tsumura (Tokyo, Japan).

Drugs and Treatments

Codeine phosphate (CPH) was purchased from Takeda Pharmaceutical (Osaka, Japan). MNG was supplied by Tsumura in the form of a powdered extract obtained by spray-drying a hot water extract mixture of the following six crude drugs: Cannabis Fructus (5.0 g), Armeniaca Semen (2.0 g), Paoniae Radix (2.0 g), Rhei Rhizoma (4.0 g), Magnoliae Cortex (2.0 g), and Aurantii Fructus Immaturus (2.0 g). CPH and MNG were dissolved in distilled water (DW) prior to oral [per os (PO)] administration. CFTR-specific inhibitor (CPTinin-172; Tocris or Sigma-Aldrich) was applied to epithelia to activate CFTR channels. After 30 minutes, when the CFTR peak current had decayed to a plateau level, the vehicle or MNG was cumulatively added (50, 100, 200, and 400 μmol/L) and short-circuit currents (n = 3) were measured using a previously reported method with slight modification (Bijvelds et al., 2009; Yang et al., 2011; Cil et al., 2016). CFTRinin-172 (20 μmol/L; Tocris or Sigma-Aldrich) was added at the end to confirm the presence of the CFTR-dependent current.

The effect of MNG on the small intestinal fluid secretion in rats was measured. DW or MNG (100, 300, and 1000 mg/kg) was administered to 24-hour fasted normal rats, and, 1 hour later, the rats were anesthetized with isoﬂurane to collect intestinal ﬂuid. The initial portion of the duodenum (pylorus) and cecum was clamped using forceps and excised, and then the intestinal fluid content between the duodenum and cecum was measured. In a parallel experiment, 24-hour fasted rats were IP injected with a CFTR-specific inhibitor (CPTinin-172, 1 mg/kg) 30 minutes before PO administration of DW or MNG (1000 mg/kg), and then the fluid content of the intestine was measured, as described above. The dose of CPTinin-172 was determined with reference to previous studies (Thiagarajah et al., 2004; Akiba et al., 2005; Mizumori et al., 2009).

Experimental Protocols

Effect of MNG on Defecation in Rats. MNG (100 or 300 mg/kg) or DW was orally administered to normal rats 2 hours before the dark cycle commenced, and the fecal count was evaluated 16 hours after administration. We chose MNG doses (100 and 300 mg/kg) that did not influence the food intake of the free-fed rats in this experiment.

The feces were dried for more than 1 day at approximately 45°C, the weight was measured, and the weight per count was calculated. The fecal characteristics were macroscopically assessed based on criteria modified in a previous report and described as follows (Bhol and Schechter, 2007): normal feces: well-formed pellets, rigid as normal; soft feces: formed pellet with moisture, soft feces that retains its shape; and diarrhea: loose feces with abnormal form, much moisture, and softer shapeless form.
Results

Effect of MNG on Defecation in Normal Rats. As shown in Fig. 1A, the fecal count for 16 hours was 38.7 ± 1.5 (N) in the control group administered DW, which was not significantly different from that of the MNG (100 or 300 mg/kg)-treated group. The fecal weight was 3.8 ± 0.1 g in the control group, whereas it was 4.9 ± 0.2 g and 5.7 ± 0.4 g in the MNG 100 and 300 mg/kg-treated groups, respectively (Fig. 1B). MNG significantly increased the fecal weight of rats in a dose-dependent manner. In addition, the results in Fig. 1C reveal that the fecal weight per count of the MNG-treated group was significantly increased in the fecal weight of rats in a dose-dependent manner. In addition, the results in Fig. 1C reveal that the fecal weight per count of the MNG-treated group was higher than that of the control group (100 and 300 mg/kg MNG, 0.13 ± 0.01 and 0.14 ± 0.01 g, \( P < 0.05 \) and 0.001, respectively, versus control, 0.10 ± 0.01 g, Dunnett’s test). No difference in food intake was observed between DW- and the MNG (100 or 300 mg/kg)-treated groups.

The fecal characteristics shown in Table 1 were all normal in the control and MNG 100 mg/kg groups. In contrast, 17.2% soft feces were observed in the MNG 300 mg/kg group (\( P < 0.01 \) versus control, Steel’s test). Furthermore, diarrhea was not observed in any of the groups.

Effect of MNG on Opioid-Induced Constipation in Rats. The fecal excretion 16 hours after administration of DW or MNG was evaluated, and the typical examples of the feces are shown in Fig. 2. The CPH + DW-treated group exhibited decreased defecation compared with that of the other groups. Fecal counts were lower in the CPH + DW-treated group (25.6 ± 1.3, \( P < 0.001 \), Steel’s test) than in the control group treated with DW alone (42.3 ± 2.4). The CPH + MNG-treated group showed significantly increased fecal counts compared with those of the CPH + DW-treated group (100 and 300 mg/kg MNG, 34.0 ± 1.9 and 34.0 ± 2.4, respectively, both \( P < 0.05 \), Steel’s test; Fig. 3A).

The fecal weight significantly decreased in the CPH + DW-treated group (2.5 ± 0.1 g, \( P < 0.01 \), Steel’s test) compared with that of the control group (3.5 ± 0.2 g), and this effect was recovered by coadministration of MNG (100 mg/kg MNG; 3.0 ± 0.1 g; 300 mg/kg MNG; 3.1 ± 0.3 g, \( P < 0.05 \), Steel’s test; Fig. 3B). Food intake did not differ significantly between groups. The evaluation of the fecal characteristics revealed that 5.0% of the total feces was soft in the CPH + MNG 300 mg/kg group (\( P < 0.01 \) versus control, Steel’s test), but that of the other groups was normal (Table 2). In addition, no diarrhea was observed in any group.

Effect of MNG on Small Intestinal Fluid Secretion in Normal Rats. The effect of MNG on the small intestinal fluid secretion in 24-hour fasted rats was assessed. As shown in Fig. 4A, the fluid content of the small intestine 1 hour after administration was 0.62 ± 0.07 g in the DW-treated control group. MNG at doses of 300 and 1000 mg/kg significantly increased the amount of the small intestinal fluid in rats (300 and 1000 mg/kg, 1.01 ± 0.11 and 1.21 ± 0.08 g, \( P < 0.05 \) and \( P < 0.001 \), respectively).

The effect of MNG on the small intestinal fluid was abolished by IP injection of the CFTRinh-172 (DW + PBS group, 0.55 ± 0.07 g; MNG + PBS group, 1.27 ± 0.10 g, \( P < 0.001 \); and MNG + CFTRinh-172 group, 0.63 ± 0.06 g, \( P < 0.001 \); Fig. 4B). In DW-treated rats, the injection of CFTRinh-172 had no effect on the small intestinal fluid (Fig. 4C).

Effects of MNG on Chloride Channel Activities and Opioid Receptors. To clarify the mechanisms of action of

<p>| TABLE 1 |
| Effects of MNG on fecal characteristics in normal rats. DW or MNG (100 or 300 mg/kg) was PO administered to normal rats 2 h before onset of dark cycle. Fecal characteristics were assessed for 16 h after administration. Data are the mean of incidence (%). |</p>
<table>
<thead>
<tr>
<th>Fecal Characteristics</th>
<th>Incidence (%)</th>
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<tbody>
<tr>
<td></td>
<td>DW</td>
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<tr>
<td>Normal</td>
<td>100</td>
</tr>
<tr>
<td>Soft</td>
<td>0</td>
</tr>
<tr>
<td>Diarrhea</td>
<td>0</td>
</tr>
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**\( P < 0.01 \) versus DW-treated normal rats using Steel’s test (\( n = 10 \)).
MNG, its effects on the CFTR chloride channel activity in NhBE were evaluated using the Ussing chamber assay. The short circuit current was negatively changed in a dose-dependent manner by the addition of MNG (50–400 μg/mL) to the cell culture. Treatment with CFTRinh-172 (20 μmol/L), a CFTR-specific inhibitor, blocked the response of MNG-treated cells, which was restored to the levels of the vehicle-treated cells (Table 3). In contrast, when the activity of the ClC-2 chloride channel was presented as percent inhibition, although an agonist effect is denoted as a negative inhibition value, it was 60.1 ± 9.4% in epithelial cells treated with 400 μg/mL MNG.

The effect of MNG on the OP3 receptor was evaluated using a radioligand-binding assay, and no effect was observed at 200 μg/mL on the binding activities of this receptor (data not shown).

Discussion

In this study, we found that administration of MNG improved opioid-induced constipation in rats. The effect of MNG was most likely mediated by an increase in the intestinal fluid secretion via CFTR chloride channel activation. First, we clarified the pharmacological effects of MNG on defecation in normal rats, and the results showed that the administration of MNG significantly increased the fecal weight, but not the count. Next, we elucidated the pharmacological effects of MNG on defecation in a CPH-treated rat model of opioid-induced constipation. The decrease in fecal count and weight in the CPH-treated rats was partially prevented by MNG administration.

Increased fecal output (frequency and volume) is one of the important factors in constipation therapy (Chokhavatia et al., 2016). Dry and hard stool causes difficult intestinal transit (Fredericks et al., 2010), and, therefore, it is desirable for feces to be softened by treatment of constipation (Canadian Agency for Drugs and Technologies in Health, 2014; Costilla and Foxx-Orenstein, 2014). In this study, the analysis of fecal characteristics revealed that MNG administration increased the incidence of soft feces in both normal and CPH-treated rats. Our previous study demonstrated that MNG increased the water content and size of feces in rats with fiber-free diet-induced constipation (Harada et al., 2016). Therefore, MNG may have facilitated defecation by softening the feces in both normal and CPH-treated rats. The present study demonstrated that MNG had no binding affinity for the OP3 receptor, suggesting that MNG improved constipation without interfering with the action of opioids.

The enhancement of the small intestinal fluid secretion is important for promoting defecation (De Lisle, 2012; Cil et al., 2016). The increased fluid secretion in the bowel lumen softens the feces and promotes bowel transit (Lacy and Levy, 2007; Chokhavatia et al., 2016). Recently, stimulation of fluid secretion by pharmacologically opening chloride channels in the epithelium of the intestinal mucosa has been considered a new approach in constipation therapy (Schiller, 2004). The selective chloride channel activator lubiprostone enhances the secretion of the small intestinal fluid and promotes the small bowel movement, leading to increased colon transit (Camilleri et al., 2006; Lacy and Levy, 2007). The GC-C receptor agonist linaclotide also increases chloride secretion and thereby

![Fig. 2. Representative example of feces in CPH-induced constipation rat model. (A) DW only, (B) CPH + DW, (C) CPH + MNG 100 mg/kg, and (D) CPH + MNG 300 mg/kg; DW or MNG were PO administered 0.5 hour after treatment with (A) DW or (B–D) CPH 12 mg/kg (PO). Feces were collected over 16 hours after DW or MNG administration.](image)

![Fig. 3. Effects of MNG on CPH-induced constipation rat model. (A) Fecal count and (B) weight were measured for 16 hours after DW or MNG administration. Data are mean ± S.E.M. *P < 0.05, **P < 0.01, and ***P < 0.001 versus CPH + DW–treated rats using Steel’s test (n = 10).](image)
induces cellular movement of sodium and water into the intestinal lumen (Jiang et al., 2015). Furthermore, it promotes the synthesis of intracellular cGMP and subsequently stimulates the cGMP-dependent protein kinase II to phosphorylate CFTR (Vaandrager et al., 1998; Sindic and Schlatter, 2006; Bryant et al., 2010). Additionally, GC-C/cGMP activation plays a role in relieving abdominal pain (Corsetti and Tack, 2013). This new approach improves the difficulty or pain associated with intestinal transit by promoting bowel movements and, therefore, may be beneficial for patients with constipation (Chokhavatia et al., 2016).

The present study demonstrates that MNG enhanced the small intestinal fluid secretion. Moreover, it may be involved in promoting bowel movements by softening feces. Therefore, to clarify the underlying mechanism of action, the effects of MNG on the chloride channels, ClC-2 and CFTR, were examined in vitro. The results revealed that MNG exhibited agonistic activity on CFTR; CFTR channels are distributed in the apical membranes of intestinal epithelial cells (Matthews, 2002; Field, 2003; Yang et al., 2011), and MNG acted locally in the intestinal tract rather than systemically. The concentration of MNG used in vivo was 30 or 60 mg/mL. Although the

<table>
<thead>
<tr>
<th>Fecal Characteristics</th>
<th>Incidence (%)</th>
</tr>
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<tbody>
<tr>
<td>Control</td>
<td>CPH + DW</td>
</tr>
<tr>
<td>Normal</td>
<td>100</td>
</tr>
<tr>
<td>Soft</td>
<td>0</td>
</tr>
<tr>
<td>Diarrhea</td>
<td>0</td>
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</table>

**P < 0.01 versus CPH + DW-treated rat using Steel's test (n = 10).
This observation suggested that Rhei suggests that this may contribute to the reversal of constipation which are present in was not likely to be involved in the increase in small promote gastrointestinal motility (Zhang et al., 2005; Yang has a critical role in the regulation of intestinal barrier Blikslager, 2015). It suggests that the ClC-2 chloride channel its distribution varies from species to species (Jin and ClC-2 is mostly located in proximity to tight junctions, activating CFTR chloride channels. Conversely, MNG did not that MNG enhanced secretion of the small intestinal fluid by activating CFTR chloride channels. Recent studies demonstrated that ClC-2 contains multiple components, but the active in- of crude drugs contained in MNG. Cannabis Fructus a large amount of fatty acid oils, including olein, linolein, and linolenin, which affect the small intestinal fluid secretion (Slot et al., 1983). Naringenin, an ingredient of Aurantii Fructus Immaturus, increased the production of cGMP by inhibiting phosphodiesterase activity (Orallo et al., 2005). These findings suggest the activation of CFTR chloride channel through cGMP signal transduction. In contrast, Rhei Rhizoma-containing drugs are widely used as laxatives (Iizuka and Hamamoto, 2015; Hirose et al., 2016). MNG also contains Rhei Rhizoma; however, it improved constipation without inducing diarrhea in rats in this study. In addition, the Kampo medicine, daioukanzo, which is composed of Rhei Rhizoma and Glycyrrhiza radix, did not have CFTR activity (data not shown). This observation suggested that Rhei Rhizoma was not likely to be involved in the increase in small intestinal fluids induced by MNG. However, Rhei Rhizoma enhances intestinal movement (Iizuka and Hamamoto, 2015; Hirose et al., 2016). It is well known that sennosides A and B, which are present in Rhei Rhizoma, are metabolized by intestinal bacteria to become rheinanthrone, which has strong laxative activity. Increased myoelectric activity and contractility in the intestine and colon by Rhizoma-containing drugs suggest that this may contribute to the reversal of constipation by promoting motility and accelerating transit. Magnolol and honokiol, which are constituents of Magnoliae Cortex, promote gastrointestinal motility (Zhang et al., 2005; Yang et al., 2008; Miao et al., 2013). Peoniflorin, a constituent of Paeoniae Radix, is known to relieve pain and may have a beneficial effect on abdominal pain in patients with constipation (Zhang et al., 2008, 2009; Xu et al., 2013). These beneficial effects that improve symptoms of patients with constipation are also likely to be synergistically involved in the efficacy of MNG. However, we did not identify the active ingredient of MNG and its specific detailed mechanism of action for corre- lating opioid receptors and CFTR; therefore, further investigation is required.

In the present study, we used a rat model in which constipation was induced by codeine, a relatively weak opioid agonist. It has been reported that the CFTR activator, phenylquinoxalinone, normalized stool output and water content in a mouse model of constipation induced by the more potent opioid agonist loperamide (Cil et al., 2016). These findings suggested that CFTR-mediated stool softening overcame opioid-induced constipation. Moreover, a clinical study of MNG on functional constipation symptoms demonstrated that most patients tolerated MNG well and no serious adverse effect was found. However, further investigation is needed to assess the safety of MNG, particularly in the elderly, who often have multiple comorbidities, and patients undergoing chemotherapy.

In summary, this study provided evidence to support an undoubtedly major role for MNG in improving constipation by, at least in part, increasing the intestinal fluid secretion through CFTR chloride channel activation.

In conclusion, we demonstrated that MNG increased the fecal output in opioid-induced constipation in rats. Further- more, our results suggested that the effects of MNG are mediated by increasing the small intestinal fluid secretion by CFTR chloride channel activation. Therefore, MNG could be used for the treatment of constipation in patients taking opioids.

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Authorship Contributions
Participated in research design: Harada, Fujitsuka.
Conducted experiments: Harada, Iizuka, Saegusa, Mogami.
Performed data analysis: Harada, Saegusa.
Wrote or contributed to the writing of the manuscript: Harada, Fujitsuka, Hattori.

References
Canadian Agency for Drugs and Technologies in Health (2014) Treatments for Con- stipation: A Review of Systematic Reviews. [Internet] Ottawa, Ontario, Canada.

**TABLE 3**

Effects of MNG on CFTR chloride channel activity evaluated using Ussing chambers assay.

<table>
<thead>
<tr>
<th>Test Article (µg/mL)</th>
<th>Short-Circuit Current (µA/cm²)</th>
</tr>
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<tbody>
<tr>
<td>Vehicle</td>
<td>0.02 ± 0.13</td>
</tr>
<tr>
<td>+CFTRinh-172</td>
<td>16.81 ± 1.31</td>
</tr>
<tr>
<td>MNG 50</td>
<td>−3.04 ± 0.26***</td>
</tr>
<tr>
<td>MNG 100</td>
<td>−5.21 ± 0.44***</td>
</tr>
<tr>
<td>MNG 200</td>
<td>−6.73 ± 0.32***</td>
</tr>
<tr>
<td>MNG 400</td>
<td>−9.85 ± 0.17***</td>
</tr>
<tr>
<td>+CFTRinh-172</td>
<td>23.10 ± 0.69</td>
</tr>
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***P < 0.01 versus vehicle by Dunnett’s test. Data are mean ± S.E.M. (n = 3).