The Antiemetic 5-HT<sub>3</sub> Receptor Antagonist Palonosetron Inhibits Substance P-Mediated Responses In Vitro and In Vivo

Camilo Rojas, Ying Li, Jie Zhang, Marigo Stathis, Jesse Alt, Ajit G. Thomas, Sergio Cantoreggi, Silvia Sebastiani, Claudio Pietra, and Barbara S. Slusher

Department of Neurology (B.S.S.) and Brain Science Institute (C.R., M.S., J.A., A.G.T., B.S.S.), Johns Hopkins University School of Medicine, Baltimore, Maryland; Division of Gastroenterology, University of Michigan, Ann Arbor, Michigan (Y.L.); Eisai Inc., Baltimore, Maryland (J.Z.); and Helsinn Healthcare, Lugano, Switzerland (S.C., S.S., C.P.)

Received January 22, 2010; accepted August 18, 2010

ABSTRACT

Palonosetron is the only 5-HT<sub>3</sub> receptor antagonist approved for the treatment of delayed chemotherapy-induced nausea and vomiting (CINV) in moderately emetogenic chemotherapy. Accumulating evidence suggests that substance P (SP), the endogenous ligand acting preferentially on neurokinin-1 (NK-1) receptors, not serotonin (5-HT), is the dominant mediator of delayed emesis. However, palonosetron does not bind to the NK-1 receptor. Recent data have revealed cross-talk between the NK-1 and 5HT<sub>3</sub> receptor signaling pathways; we postulated that if palonosetron differentially inhibited NK-1/5-HT<sub>3</sub> cross-talk, it could help explain its efficacy profile in delayed emesis. Consequently, we evaluated the effect of palonosetron, granisetron, and ondansetron on SP-induced responses in vitro and in vivo. NG108-15 cells were preincubated with palonosetron, granisetron, or ondansetron; antagonists were removed and the effect on serotonin enhancement of SP-induced calcium release was measured. In the absence of antagonist, serotonin enhanced SP-induced calcium-ion release. After preincubation with palonosetron, but not ondansetron or granisetron, the serotonin enhancement of the SP response was inhibited. Rats were treated with cisplatin and either palonosetron, granisetron, or ondansetron. At various times after dosing, single neuronal recordings from nodose ganglia were collected after stimulation with SP; nodose ganglia neuronal responses to SP were enhanced when the animals were pretreated with cisplatin. Palonosetron, but not ondansetron or granisetron, dose-dependently inhibited the cisplatin-induced SP enhancement. The results are consistent with previous data showing that palonosetron exhibits distinct pharmacology versus the older 5-HT<sub>3</sub> receptor antagonists and provide a rationale for the efficacy observed with palonosetron in delayed CINV in the clinic.

Introduction

Nausea and vomiting are common, severe, and feared side effects of many chemotherapeutics. Inadequate control of chemotherapy-induced nausea and vomiting (CINV) impairs functional activity and may compromise adherence to treatment. 5-HT<sub>3</sub> receptor antagonists are most efficacious against acute emesis (0–24 h after chemotherapy administration), whereas neurokinin-1 (NK-1) receptor antagonists have been associated with the prevention of delayed emesis (24–120 h after chemotherapy administration) (Hesketh et al., 2003). Even though the terms acute and delayed are approximations with no clear distinction of when acute emesis ends and delayed emesis begins, they point to the idea that different mechanisms are at play. Palonosetron is unique among 5-HT<sub>3</sub> receptor antagonists in that, in addition to being effective against acute emesis, it has shown efficacy against delayed emesis (Eisenberg et al., 2003; Aapro et al., 2006; Saito et al., 2009). The reason for this unique efficacy in delayed emesis is not clear, because palonosetron does not bind to NK-1 receptors (Wong et al., 1995).

Receptor cross-talk, defined as activation of one receptor by its ligand affecting cellular responses to another receptor system, has been well described. Recent reports in the literature have shown that there is cross-talk between NK-1 and 5-HT<sub>3</sub> receptor signaling pathways. For example, substance...
Palonosetron Inhibits SP-Mediated Responses

P (SP), an agonist at the NK-1 receptor, was shown to poten-
tiate 5-HT₃ receptor-mediated inward current in rat trigem-
inal ganglion neurons (Hu et al., 2004). In separate studies, 5-HT₃ receptor antagonists were shown to block SP-mediated
gastric afferent activation (Minami et al., 2001). In addition, NK-1 antagonism blocked serotonin-induced vagal afferent
activation (Minami et al., 2001). Evidence of receptor signal-
ing cross-talk raises the interesting possibility that palono-
setron’s unique efficacy in delayed emesis could be caused by
differential inhibition of the 5-HT₃/NK-1 receptor cross-talk.
In the present work, we evaluated the effect of palonosetron, granisetron, and ondansetron on SP-induced responses in
vitro and in vivo. We report that palonosetron inhibited the
serotonin enhancement of the SP response in NG108-15 cells and the cisplatin enhancement of the neuronal response to
SP in rat nodose ganglia. This inhibition was not observed
with ondansetron or granisetron, two other widely used
5-HT₃ receptor antagonists. The results suggest palono-
setron differentially inhibits 5-HT₃/NK-1 receptor signaling
cross-talk and provide a rationale to explain palonosetron’s
unique efficacy against delayed emesis in the clinic.

Materials and Methods

Calcium-Ion Release Measurements in NG108-15 Cells. NG108-15 cells, known to express both 5-HT₃ and NK-1 receptors,
were grown in high-glucose Dulbecco’s modified Eagle’s medium supplemented with a mixture of sodium hypoxanthine, aminopterin,
and thymidine, 10% heat-inactivated fetal bovine serum, and 2 mM
glutamine to 90% confluence. Cells were incubated with palonose-
tron (10 nM), granisetron (60 nM), and ondansetron (300 nM) for 2 h.
Antagonist concentrations were approximately 50-fold
higher than the EC₅₀ values described previously in NG108-15 or N1E-115 cells (Wong et al.,
1995; Rojas et al., 2008). Subsequently, antagonists were removed
and ondansetron or granisetron, two other widely used
5-HT₃ receptor antagonists. The results suggest palono-
setron differentially inhibits 5-HT₃/NK-1 receptor signaling
cross-talk and provide a rationale to explain palonosetron’s
unique efficacy against delayed emesis in the clinic.

Results

Palonosetron, but Not Ondansetron or Granisetron, Inhibited Serotonin Enhancement of SP-Induced Calcium-Ion Release in NG108-15 Cells. Calcium-ion release in NG-108-15 cells depended on SP
response was not affected by prior incubation with ondanse-
tron or granisetron; EC₅₀ values were the same as those
obtained with SP plus serotonin (Fig. 1, B and C; Table 1). In
contrast, preincubation with palonosetron inhibited the
serotonin enhancement of the SP response; the EC₅₀ shifted
6-fold to the right to 3.7 ± 0.84 M (data not shown). Serotonin enhancement of the SP response was not affected by prior incubation with ondansetron or granisetron; EC₅₀ values were the same as those
obtained with SP plus serotonin (Fig. 1, B and C; Table 1). In
contrast, preincubation with palonosetron inhibited the
serotonin enhancement of the SP response; the EC₅₀ shifted
6-fold to the right to 3.7 ± 0.84 M (Fig. 1D; Table 1).

Cisplatin Enhanced Neuronal Response to SP in Nodose Ganglia. The resting discharge of single nodose
neurons after intra-arterial injection of vehicle was
negligible (<1 impulse/10s). When SP was administered at

Animal Preparation. Studies were conducted in accordance with
the Declaration of Helsinki and the Guide for the Care and Use of
Laboratory Animals as adopted and promulgated by the National
Institutes of Health. Experiments were performed on adult male
Sprague-Dawley rats weighing 270 to 350 g. Animals were housed in
an animal facility with limited access. Room temperature was 22 ±
2°C, and relative humidity was set at 55 ± 10%. Artificial lighting
was provided for 24 h with a cycle of 12-h light/12-h dark (light 7
AM–7 PM). Animals had free access to food and water; they were
anesthetized with an intraperitoneal injection of a mixture of
chloral hydrate (80 mg/kg) and urethane (800 mg/kg). The anesthetic
was supplemented every 3.5 h with an intravenous dose of 1/3 of the initial
dose. Adequate depth of anesthesia was established in prior experi-
ments by monitoring heart rate and withdrawal reflexes after sub-
cutaneous electrical stimulation or pinching of the skin. Animals
were ventilated with a respirator; a tracheal tube permitted artificial
ventilation with room air (75–85 strokes/min, 3.5–4.0 cm³ tidal
volumes). A midline abdominal incision exposed the abdominal va-
gus, the stomach, and the duodenum. Stimulation of the subdia-
phragmatic vagus nerve was accomplished by placing a pair of
Teflon-coated, pure-gold wire electrodes (outside diameter, 76 μm)
around the anterior and posterior trunks, approximately 2 to 3 cm
above the gastroesophageal junction, and above the accessory
and celiac branches of the vagus nerve. These electrodes were loosely
sutured to the esophagus to limit displacement.

Drug Dosing. Cisplatin (5 mg/kg) was given intraperitoneally, SP
(10 μg/kg) was given by intra-arterial injection, and antagonists
were administered by intravenous infusion. Antagonists were
dissolved in 0.9% saline solutions and infused at a rate of 0.085 ml/min.
Total dose of 38 mg/kg for ondansetron was administered over 30
min in 360 μg/100-μl solution. Total dose of 840 μg/kg for granisetron
was administered over 10 min in 24 μg/100-μl solution. Total doses
of 30, 100, and 300 μg/kg for palonosetron were administered over 10
min in 0.9, 3, and 9 μg/100-μl solutions, respectively.

Statistical Analysis. Prism (GraphPad Software Inc., San Diego,
CA) was used to obtain EC₅₀ values in vitro experiments (sigmoi-
dal dose-response variable slope). Errors correspond to S.E.M. of at
least eight independent determinations. Student’s t test (two-tailed
distribution) was used to determine p values. Experimental groups
in the in vivo experiments included at least 12 independent neuronal
measurements from at least seven rats to obtain average values.
Error bars correspond to S.E.M.

Results

Palonosetron, but Not Ondansetron or Granisetron, Inhibited Serotonin Enhancement of SP-Induced Calcium-Ion Release in NG108-15 Cells. Cisplatin was used to obtain EC₅₀ values in in vitro experiments (sigmoi-
dal dose-response variable slope). Errors correspond to S.E.M. of at
least eight independent determinations. Student’s t test (two-tailed
distribution) was used to determine p values. Experimental groups
in the in vivo experiments included at least 12 independent neuronal
measurements from at least seven rats to obtain average values.
Error bars correspond to S.E.M.
10 µg/kg via intra-arterial injection neuronal activity was increased, although variable, to 4 ± 4 impulses/10 s. When measurement of the SP response was made 10 h after intra-peritoneal administration of 5 mg/kg i.p. cisplatin (Fig. 2A), SP responses increased to 23 ± 3 impulses/10 s. When the dose of cisplatin was increased to 10 mg/kg, both basal and SP responses were similar within experimental error to when 5 mg/kg cisplatin was used (Fig. 2B). In short, there was an approximately 6-fold increase in the neuronal response to SP in the presence of 5 to 10 mg/kg cisplatin.

**Palonosetron Dose-Dependently Inhibited Cisplatin’s Potentiation of the SP Response in Nodose Ganglia.** Preliminary studies with the three antagonists suggested that only palonosetron had an effect on SP responses. Consequently, we conducted a dose response with palonosetron. Cisplatin (5 mg/kg i.p.) was administered to rats; 10 h later, single nodose ganglia neurons were isolated and four electrophysiological recordings were made at 10-min intervals (Fig. 3A). First, a basal reading was taken. Second, the neuronal response to SP (10 µg/kg intra-arterial injection) was measured. Third, the neuronal response to palonosetron (intravenous infusion of 30, 100, and 300 µg/kg) was measured. The fourth and final recording measured neuronal responses after the administration of SP (10 µg/kg intra-arterial injection). The first three responses were similar throughout the experiment: basal readings were 7.5 ± 3

---

**Fig. 1.** The effect of 5-HT3 receptor antagonists on serotonin activation of SP-induced intracellular calcium-ion release. A, serotonin activation of the SP response. NG108-15 cells were incubated with SP at various concentrations, and after 1 h internal calcium release was measured upon the addition of serotonin (10⁻⁷ M). B, ondansetron (Ondan; 30 nM); C and palonosetron (Palo; 1 nM; D) were used. Error bars correspond to ± S.E.M.; error bars in B–D for the SP and SP + 5HT traces are the same as in A. Each EC₅₀ curve corresponds to the average of at least eight independent determinations.

**Fig. 2.** The effect of cisplatin on neuronal response to SP stimulation. A, experimental protocol. Cisplatin was given at 0 h; 10 h later, basal and SP responses were measured. B, animals were anesthetized after cisplatin administration, vagal nerve was isolated, and single neuronal responses were examined. Before SP stimulation basal discharge frequency (impulses/10 s) was assessed for 1 min. The discharge frequency after SP administration was subsequently measured for 3 min. Results are the average of at least 12 independent neuronal measurements from at least seven rats (***p < 0.001; compared with no cisplatin). Error bars correspond to ± S.E.M.

---

**TABLE 1**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>EC₅₀ ± S.E.M.</th>
<th>µM</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SP + 5-HT</td>
<td>6.7 ± 0.97</td>
<td></td>
</tr>
<tr>
<td>SP + 5-HT + ondansetron</td>
<td>0.62 ± 0.09</td>
<td></td>
</tr>
<tr>
<td>SP + 5-HT + granisetron</td>
<td>0.66 ± 0.17</td>
<td></td>
</tr>
<tr>
<td>SP + 5-HT + palonosetron</td>
<td>0.57 ± 0.10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.7 ± 0.84</td>
<td></td>
</tr>
</tbody>
</table>
The doses used for ondansetron and granisetron in these studies turned out to be in excess of their active doses reported in previous efficacy studies in animals (Eglen et al., 1995; Rudd and Naylor, 1996; Endo et al., 1999; Rudd et al., 2002). Vagal nerve activity was measured in animals 10 h after cisplatin administration (5 mg/kg i.p.). The same measurements as in the palonosetron dose-dependence experiment were made: basal response to SP, response to each antagonist alone, and response to administration of SP (Fig. 4A). Basal and SP responses were 8 ± 3 and 33 ± 6 impulses/10 s, respectively. Neither ondansetron (38 mg/kg i.v.) nor granisetron (840 μg/kg i.v.) had an effect on the basal response. When SP was administered after ondansetron or granisetron, the SP response was not affected. This lack of effect was in stark contrast to more than 70% inhibition of the SP response after palonosetron administration (Fig. 4B).

**Palonosetron’s Inhibition of the Cisplatin-Induced SP Response Was Time-Dependent.** One major consideration in these experiments and in the clinic is the time of administration of 5-HT\textsubscript{3} receptor antagonist with respect to the time of administration of the chemotherapeutic agent. In the experiments described thus far, the antagonists were administered 10 h after cisplatin. We wanted to explore whether inhibition of the SP response could be observed at earlier time points. To this end, we explored the inhibition of the neuronal response to SP when antagonists were administered 30 min before and 5 and 10 h after cisplatin. As above, the measurement of the neuronal response to SP was made 10 h after cisplatin (Fig. 5A). The neuronal response to SP administration in the presence of cisplatin was 32 ± 4 impulses/10 s. When ondansetron (38 mg/kg i.v.) or granisetron (840 μg/kg i.v.) was given at either 30 min before or 5 and 10 h after cisplatin, there was no effect on the SP response. In contrast, when palonosetron (300 μg/kg i.v.) was administered at 30 min before or 5 and 10 h after cisplatin, inhibition of the SP response was observed at every time point. There was 33 ± 7% inhibition when palonosetron was administered 30 min before cisplatin, 70 ± 8% inhibition when palonosetron was given 5 h after cisplatin, and 78 ± 10% inhibition when palonosetron was given 10 h after cisplatin (Fig. 5B).

**Discussion**

5-HT\textsubscript{3} and NK-1 receptor antagonists are common therapy to help prevent CINV. In general, 5-HT\textsubscript{3} receptor antagonists are efficacious in the acute (0–24 h) phase of CINV, whereas NK-1 receptor antagonists are most efficacious during the delayed (24–120 h) phase (Hesketh et al., 2003). Palonosetron is the only 5-HT\textsubscript{3} receptor antagonist that is labeled for the treatment of delayed emesis in moderately emetogenic chemotherapy. The mechanisms by which palonosetron helps prevent delayed emesis are not known; this is tantalizing given that palonosetron does not bind to the NK-1 receptor (Wong et al., 1995). On the other hand, palonosetron has been shown to exhibit unique molecular interactions with the 5-HT\textsubscript{3} receptor. Palonosetron exhibits allosteric binding and positive cooperativity (Rojas et al., 2008) and triggers receptor internalization and long-term inhibition of receptor function (Rojas et al., 2010), attributes not shared by other 5HT\textsubscript{3} receptor antagonists.

Various reports in the literature have shown that there is cross-talk between NK-1 and 5-HT\textsubscript{3} receptor signaling path-
ways (Hu et al., 2004). SP, a known agonist at the NK-1 receptor, was shown to potentiate 5-HT₃ receptor-mediated inward current in rat trigeminal ganglion neurons. Potentiation of 5-HT₃ receptor current through SP is thought to involve second-messenger signaling that culminates in protein kinase C activation (Hu et al., 2004). In addition, 5-HT₃ receptor antagonists have been shown to block SP-mediated vagal afferent activation, and NK-1 antagonists were shown to block serotonin-induced vagal afferent activation (Minami et al., 2001). Evidence of receptor signaling interaction raises the interesting possibility that palonosetron’s unique efficacy to inhibit serotonin-induced vagal afferent activation could be caused by differential inhibition of the 5-HT₃/NK-1 receptor cross-talk. In the present work, we evaluated the effect of palonosetron, granisetron, and ondansetron on SP-induced responses in vitro and in vivo.

NG108-15 cells were used in the in vitro studies because they are known to express both 5-HT₃ and NK-1 receptors (Reiser and Hamprecht, 1989; Emerit et al., 1993). Previous studies have also shown that SP, acting through the NK-1 receptor, stimulates an increase of intracellular calcium ions through a release of intracellular calcium-ion stores in Chinese hamster ovary cells (Garland et al., 1996). Consequently, we determined the dependence of intracellular calcium-ion release on SP concentration and the potential synergistic response in the presence of serotonin in NG108-15 cells. Intracellular calcium-ion release depended on SP concentration (EC₅₀ = 6.7 ± 0.97 μM). In addition, serotonin, at a subthreshold concentration (10⁻⁷M), where it did not elicit calcium-ion mobilization by itself, induced a 10-fold potency increase of the response to SP alone (EC₅₀ = 0.62 ± 0.09 μM; Fig. 1A; Table 1). This result was in agreement with previous findings pointing to interactions between the signaling of 5-HT₃ and NK-1 receptors in rat trigeminal ganglion neurons, where serotonin potentiation of inward current was enhanced by SP preapplication (Hu et al., 2004). Further, NG108-15 cells provided a simple in vitro system to evaluate the potential differential inhibition of 5-HT₃/NK1 receptor cross-talk by 5-HT₃ receptor antagonists. We have shown that palonosetron triggers long-term 5-HT₃ receptor internalization, whereas ondansetron and granisetron exhibit simple receptor blockade (Rojas et al., 2010). The purpose of these in vitro experiments was to determine whether preincubation with the 5-HT₃ antagonists, followed by their complete removal from the media, could have a persistent downstream effect on SP function. In other words, could 5-HT₃ receptor internalization affect serotonin’s activation of SP-induced calcium-ion release? To ensure excess drug availability for receptor saturation, we chose to use antagonists’ concentrations >15-fold their respective IC₅₀ values needed to inhibit serotonin-induced calcium-ion influx (Supplemental Methods and Supplemental Fig. 1, A–C; IC₅₀s were 0.7, 2, and 3 nM for palonosetron, granisetron, and ondansetron, respectively). These concentrations were also approximately 50 times their previously determined Kᵯ values (Wong et al., 1995; Rojas et al., 2010). When cells were preincubated with excess palonosetron (10 nM) followed by the drug’s removal
tron’s distinctive ability to induce 5-HT₃ receptor internalization and cause long-term reduction in 5-HT₃ receptor density on the cell surface. Previously, we have shown palonosetron rapidly partitions inside cells along with the 5-HT₃ receptor during antagonist preincubation; once inside the cell, palonosetron does not reappear in the extracellular milieu for at least 2 h. It is noteworthy that palonosetron’s internalization depends on the presence of the 5-HT₃ receptor, because palonosetron was shown not to partition into cells that do not express the 5-HT₃ receptor (Rojas et al., 2010). These data suggest that palonosetron’s unique effect on inhibition of serotonin-induced SP activation is a 5-HT₃ receptor-mediated difference, not a cell permeability difference.

To determine whether the in vitro results could also be demonstrated in vivo, we examined neuronal responses in nodose ganglia to SP after cisplatin administration in rats. We used rat nodose ganglia because they have been shown to express both 5-HT₃ and NK-1 receptors (Hu et al., 2004) and to explore the effect of 5-HT₃ receptor antagonists on the cisplatin-induced neuronal response to SP. A, experimental protocol. Ondansetron, granisetron, and palonosetron were given 0.5 h before cisplatin and 5 and 10 h after cisplatin. Four separate groups of animals were used: 1) cisplatin control, 2) ondansetron, granisetron, or palonosetron administered 0.5 h before cisplatin, 3) 5 h after cisplatin, and 4) 10 h after cisplatin. Response to SP was measured 10 h after cisplatin administration. B, SP response after each antagonist was administered at different times with respect to cisplatin (cis). Results are the average of at least 12 independent neuronal measurements from at least seven rats (*, p < 0.05; ***, p < 0.001; compared with cisplatin). Error bars correspond to ± S.E.M.

Fig. 5. Effect of time of administration of 5-HT₃ receptor antagonists on the cisplatin-induced neuronal response to SP. A. A, experimental protocol. Ondansetron, granisetron, and palonosetron were given 0.5 h before cisplatin and 5 and 10 h after cisplatin. Four separate groups of animals were used: 1) cisplatin control, 2) ondansetron, granisetron, or palonosetron administered 0.5 h before cisplatin, 3) 5 h after cisplatin, and 4) 10 h after cisplatin. Response to SP was measured 10 h after cisplatin administration. B, SP response after each antagonist was administered at different times with respect to cisplatin (cis). Results are the average of at least 12 independent neuronal measurements from at least seven rats (*, p < 0.05; ***, p < 0.001; compared with cisplatin). Error bars correspond to ± S.E.M.
binding followed by dissociation at the receptor on the cell surface as occurs with ondansetron and granisetron. Because the time of antiemetic administration could have different effects on cisplatin-induced toxicity in the clinic, we also explored the time dependence of palonosetron inhibition of the cisplatin-induced neuronal response to SP and the potential that ondansetron and/or granisetron could also have an effect if administered at times other than 10 h after cisplatin administration. Additional studies were performed when antagonists were given 30 min before cisplatin and 5 h after cisplatin. When ondansetron or granisetron was used, no inhibition of the cisplatin effect was observed at either time point. In contrast, when palonosetron was administered 30 min before cisplatin or 5 h after cisplatin and the effect on SP activity was measured 10 h later 33 ± 7 and 70 ± 8% inhibition was observed, respectively (Fig. 5). In short, palonosetron inhibition of the SP response could be seen when palonosetron was administered 10 h, 5 h, or 10 min before measurement of the SP response.

The half-life of palonosetron in the rat is 90 min after intravenous administration (Supplemental Data, Palonosetron Rat PK Report), which is in the same order of magnitude as the half-lives previously reported for ondansetron (20–40 min) (Yang and Lee, 2008) and granisetron (50 min) (Huang et al., 1999) in rats. Therefore, the differences we observed probably are not caused by differences in pharmacokinetics.

In summary, palonosetron uniquely inhibits cross-talk between the 5-HT3 and NK-1 receptor pathways in a dose- and time-dependent fashion. Our results are consistent with previous data showing that palonosetron exhibits distinct pharmacology versus the older 5-HT3 receptor antagonists and provide a rationale for the unique efficacy observed with palonosetron in delayed CINV in the clinic.

References


Address correspondence to: Dr. Barbara S. Slusher, The Brain Science Institute, Johns Hopkins University School of Medicine, 855 N. Wolfe Street, Suite 370, Baltimore, MD 21205. E-mail: bslusher@jhmi.edu

Downloaded from jpet.aspetjournals.org at September 13, 2017