

# Effects of the Allosteric Antagonist 1-(4-Chlorophenyl)-3-[3-(6-pyrrolidin-1-ylpyridin-2-yl)phenyl]urea (PSNCBAM-1) on CB<sub>1</sub> Receptor Modulation in the Cerebellum<sup>[S]</sup>

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## ABSTRACT

1-(4-Chlorophenyl)-3-[3-(6-pyrrolidin-1-ylpyridin-2-yl)phenyl] urea (PSNCBAM-1) has recently been described as a cannabinoid CB<sub>1</sub> receptor allosteric antagonist associated with hypophagic effects in vivo; however, PSNCBAM-1 effects on CB<sub>1</sub> ligand-mediated modulation of neuronal excitability remain unknown. Here, we investigate PSNCBAM-1 actions on CB<sub>1</sub> receptor-stimulated guanosine 5'-O-(3-[<sup>35</sup>S]thio)triphosphate ([<sup>35</sup>S]GTPγS) binding in cerebellar membranes and on CB<sub>1</sub> ligand modulation of pre-synaptic CB<sub>1</sub> receptors at inhibitory interneuron-Purkinje cell synapses in the cerebellum using whole-cell electrophysiology. PSNCBAM-1 caused noncompetitive antagonism in [<sup>35</sup>S]GTPγS binding studies, with higher potency against the CB receptor agonist (–)-*cis*-3-[2-hydroxy-4-(1,1-dimethyl heptyl)phenyl]-*trans*-4-(3-hydroxypropyl)cyclohexanol (CP55940) than for *R*(+)-[2,3-dihydro-5-methyl-3-[(morpholinyl)methyl]-pyrrolo[1,2,3-*de*]-1,4-benzoxazinyl]-(1-naphthalenyl)methanone mesylate [WIN55,212-2 (WIN55)]. In electrophysiological studies, WIN55 and CP55940 reduced miniature inhibitory postsynaptic currents (mIPSCs) frequency but not amplitude. PSNCBAM-1 application alone had no effect on mIPSCs; how-

ever, PSNCBAM-1 pretreatment revealed agonist-dependent functional antagonism, abolishing CP55940-induced reductions in mIPSC frequency but having no clear effect on WIN55 actions. The CB<sub>1</sub> antagonist/inverse agonist *N*-(piperidin-1-yl)-1-(2,4-dichlorophenyl)-5-(4-iodophenyl)-4-methyl-1*H*-multipyrazole-3-carboxamide (AM251) increased mIPSC frequency beyond control; this effect was reversed by PSNCBAM-1. PSNCBAM-1 pretreatment also attenuated AM251 effects. Thus, PSNCBAM-1 reduced CB<sub>1</sub> receptor ligand functional efficacy in the cerebellum. The differential effect of PSNCBAM-1 on CP55940 versus WIN55 actions in [<sup>35</sup>S]GTPγS binding and electrophysiological studies and the attenuation of AM251 effects are consistent with the ligand-dependence associated with allosteric modulation. These data provide the first description of functional PSNCBAM-1 allosteric antagonist effects on neuronal excitability in the mammalian central nervous system (CNS). PSNCBAM-1 allosteric antagonism may provide viable therapeutic alternatives to orthosteric CB<sub>1</sub> antagonists/inverse agonists in the treatment of CNS disease.

## Introduction

Numerous G protein-coupled receptors (GPCRs) contain allosteric binding sites for endogenous and synthetic ligands

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that are topographically different from the orthosteric site (Christopoulos and Kenakin, 2002; Christopoulos, 2002; May and Christopoulos, 2003). On the basis of the ternary complex model, ligands at such allosteric sites mediate their cooperative effects on orthosteric affinity by altering rates of orthosteric ligand association and/or dissociation from the receptor (Ehlert, 1988; Christopoulos and Kenakin, 2002; May et al., 2004, 2007). Various therapeutic advantages of allosteric over orthosteric modulation have been suggested based on the differences between their underlying mecha-

**ABBREVIATIONS:** GPCR, G protein-coupled receptor; AM251, *N*-(piperidin-1-yl)-1-(2,4-dichlorophenyl)-5-(4-iodophenyl)-4-methyl-1*H*-multipyrazole-3-carboxamide; CP55940, (–)-*cis*-3-[2-hydroxy-4-(1,1-dimethyl heptyl)phenyl]-*trans*-4-(3-hydroxypropyl)cyclohexanol; PSNCBAM-1, 1-(4-chlorophenyl)-3-[3-(6-pyrrolidin-1-ylpyridin-2-yl)phenyl]urea; WIN55,212-2 (WIN55), *R*(+)-[2,3-dihydro-5-methyl-3-[(morpholinyl)methyl]-pyrrolo[1,2,3-*de*]-1,4-benzoxazinyl]-(1-naphthalenyl) methanone mesylate; IN, interneuron; PC, Purkinje cell; mIPSC, miniature inhibitory postsynaptic current; CB, cannabinoid; aCSF, artificial cerebrospinal fluid; TTX, tetrodotoxin; ANOVA, analysis of variance; HSD, honestly significant difference; Δ<sup>9</sup>-THCV, Δ<sup>9</sup>-tetrahydrocannabivarin; NBQX, 2,3-dihydroxy-6-nitro-7-sulfamoylbenzo(f)quinoxaline; SR141716A, *N*-(piperidin-1-yl)-5-(4-chlorophenyl)-1-(2,4-dichlorophenyl)-4-methyl-1*H*-pyrazole-3-carboximide hydrochloride; [<sup>35</sup>S]GTPγS, guanosine 5'-O-(3-[<sup>35</sup>S]thio)triphosphate; O-1602, 5-methyl-4-[(1*R*,6*R*)-3-methyl-6-(1-methylethenyl)-2-cyclohexen-1-yl]-1,3-benzenediol.

nisms (May and Christopoulos, 2003). Price et al. (2005) identified three Organon compounds—Org 27569 (5-chloro-3-ethyl-1*H*-indole-2-carboxylic acid [2-(4-piperidin-1-yl-phenyl)-ethyl]-amide), Org 27759 (3-ethyl-5-fluoro-1*H*-indole-2-carboxylic acid [2-(4-dimethylamino-phenyl)-ethyl]-amide), and Org 29647 (5-chloro-3-ethyl-1*H*-indole-2-carboxylic acid (1-benzyl-pyrrolidin-3-yl)-amide, 2-enedioic acid salt)—as allosteric modulators at CB<sub>1</sub> receptors, thereby revealing a CB<sub>1</sub> allosteric binding site that could hold potential as an alternative target for therapeutic modulation. Horswill et al. (2007) have described the actions of a further novel CB<sub>1</sub> allosteric antagonist, 1-(4-chlorophenyl)-3-[3-(6-pyrrolidin-1-ylpyridin-2-yl)phenyl]urea (PSNCBAM-1). The Organon compounds and PSNCBAM-1 all showed ligand-dependent effects in that they increased agonist (–)-*cis*-3-[2-hydroxy-4-(1,1-dimethylheptyl)phenyl]-*trans*-4-(3-hydroxypropyl)cyclohexanol (CP55940) equilibrium binding but decreased antagonist rimonabant (SR141716A) binding. Interestingly, and so far unique to CB<sub>1</sub> receptors, allosteric modulation of orthosteric efficacy occurs in a direction opposite to the effects on orthosteric binding affinity in these studies; thus, CB<sub>1</sub> allosteric antagonists produced noncompetitive functional antagonism of CB<sub>1</sub> agonist effects (Ross, 2007a,b). PSNCBAM-1 was also suggested to exhibit agonist-dependent actions on the basis that antagonism of human CB<sub>1</sub> stimulation by different agonists exhibited a wide range of potencies in a yeast reporter assay (Horswill et al., 2007). Finally, CB<sub>1</sub> allosteric antagonism was proposed to be of functional relevance, as PSNCBAM-1 was also shown to possess hypophagic activity *in vivo* (Horswill et al., 2007).

It has yet to be determined whether CB<sub>1</sub> allosteric antagonists influence functional CB<sub>1</sub>-mediated modulation of neuronal excitability in the CNS. CB<sub>1</sub> receptors are prominently expressed on presynaptic terminals within the CNS, in which they are intimately involved in the dynamic modulation of transmitter release. Therefore, we have investigated PSNCBAM-1 modulation of the effects of exogenous ligands on synaptic transmission at the well characterized inhibitory pathway between molecular layer interneurons (INs) and Purkinje cells (PCs). We and others have demonstrated that CB<sub>1</sub> receptor activation at IN-PC synapses reduces inhibitory neurotransmission (Llano et al., 1991; Takahashi and Linden, 2000; Diana et al., 2002; Diana and Marty, 2003; Kawamura et al., 2006; Yamasaki et al., 2006; Kelm et al., 2008; Ma et al., 2008). We have also previously combined patch-clamp and multielectrode array electrophysiological recording techniques to show that CB<sub>1</sub> receptor ligand effects on inhibitory neurotransmission at IN-PC synapses functionally modulate cerebellar network activity (Ma et al., 2008). In particular, CB<sub>1</sub> receptor antagonist action at IN-PC synapses is consistent with block of endocannabinoid tone to increase GABA release and reduce overall excitability in the cerebellum (Stephens, 2009). The recent clinical withdrawal of rimonabant, an agent shown to function as an inverse agonist at CB<sub>1</sub> receptors, has been linked to an inhibition of constitutive CB<sub>1</sub> activity, which can occur even in the absence of endocannabinoid release (Jones, 2008). Such potentially unfavorable actions could be avoided by the use of neutral antagonists, which will only block the action of endocannabinoids released “on demand.” However, a further attractive option is the development of allosteric CB<sub>1</sub> receptor antagonists to offer alternative therapeutic poten-

tial to orthosteric antagonists/inverse agonists (Ross, 2007a,b). Moreover, because PC axons represent the sole efferent system from the cerebellar cortex, the present study provides an opportunity to determine whether CB<sub>1</sub> allosteric antagonists have the potential to functionally modulate the output of the cerebellum.

Here, we show that PSNCBAM-1 causes an agonist-dependent functional antagonism of CB<sub>1</sub> receptor-mediated modulation of inhibitory neurotransmission at IN-PC synapses, consistent with the demonstration of noncompetitive antagonism and agonist-dependent potency in [<sup>35</sup>S]GTPγS binding studies in isolated cerebellar membranes. We extend data to PSNCBAM-1 effects to actions on the CB<sub>1</sub> receptor antagonist/inverse agonist *N*-(piperidin-1-yl)-1-(2,4-dichlorophenyl)-5-(4-iodophenyl)-4-methyl-1*H*-multipyrazole-3-carboxamide (AM251). The reduction in CB<sub>1</sub> receptor ligand-mediated functional efficacy in the cerebellum also extends previous studies demonstrating a unique response profile for CB<sub>1</sub> allosteric antagonists to actions on neuronal excitability.

## Materials and Methods

### [<sup>35</sup>S]GTPγS Binding Assays

Cerebellar membranes were prepared from C57BL/6 mice, and [<sup>35</sup>S]GTPγS binding experiments were performed as described previously (Horswill et al., 2007; Dennis et al., 2008). In brief, 10 μg of membranes per reaction was incubated with 10 μM GDP and 0.1 nM [<sup>35</sup>S]GTPγS in assay buffer (20 mM HEPES, 3 mM MgCl<sub>2</sub>, 100 mM NaCl, 1 mM dithiothreitol, 100 nM 8-cyclopentyl-1,3-dipropylxanthine, and 1 mg/ml bovine serum albumin, pH 7.4). 8-Cyclopentyl-1,3-dipropylxanthine, an adenosine A<sub>1</sub> receptor antagonist, was included in the buffer to reduce non-CB<sub>1</sub> receptor-mediated [<sup>35</sup>S]GTPγS binding. Reactions were performed in duplicate or triplicate in 96-well, round-bottomed plates in a final volume of 200 μl; nonspecific binding was determined using 10 μM unlabeled GTPγS. Antagonists were preincubated with membranes for 10 min at room temperature before adding agonists. After addition of agonists, plates were incubated for a further 15 min at room temperature (22–24°C) before adding [<sup>35</sup>S]GTPγS. Plates were then incubated at 30°C for a further 45 min. Reactions were terminated by rapid filtration onto GF/B filter mats, which were subsequently washed five times with 300 μl/well of 50 mM Tris-HCl buffer, pH 7.4. Filter mats were dried, and scintillation reagent was added before counting radioactivity using a PerkinElmer scintillation counter (PerkinElmer Life and Analytical Sciences, Waltham, MA). PSNCBAM-1 effects were tested against a range of CB agonist concentrations. Dose-titration effects were also tested against a fixed agonist concentrations, as allowed by the noncompetitive nature of antagonism; thus, CP55940 (150 nM) or *R*(+)-[2,3-dihydro-5-methyl-3-[(morpholinyl)methyl]-pyrrolo[1,2,3-*de*]-1,4-benzoxazinyl]-(1-naphthalenyl)methanone mesylate [WIN55,212-2 (WIN55)] (0.5 μM) was used to stimulate [<sup>35</sup>S]GTPγS binding (to approximately 165% of basal) in the presence of a range of PSNCBAM-1 concentrations. Binding data were analyzed using Prism 5 (GraphPad Software Inc., San Diego, CA). Unpaired Student's *t* tests were used to compare different agonist treatment values and pIC<sub>50</sub> values.

## Electrophysiology

**Preparation of Acute Cerebellar Brain Slices.** Three- to five-week-old male C57BL/6 mice were used for all experiments, which followed methods outlined previously (Ma et al., 2008). All work was conducted in accordance with UK Home Office regulations [Animals (Scientific Procedures) Act 1986] and every effort was made to minimize any discomfort experienced by animals. Mice were killed by cervical dislocation and decapitated. The brain was rapidly removed and submerged in ice-cold sucrose-based aCSF solution. The cerebellum was then hemisected along the midline and a hemisphere glued to the stage of a Vibratome (R and L Slaughter, Upminster, UK) that was used to prepare 300- $\mu$ m parasagittal cerebellar slices. After sectioning, each slice was immediately moved to a holding chamber containing standard aCSF, which consisted of 124 mM NaCl, 3 mM KCl, 26 mM NaHCO<sub>3</sub>, 2.5 mM NaH<sub>2</sub>PO<sub>4</sub>, 2 mM MgSO<sub>4</sub>, 2 mM CaCl<sub>2</sub>, and 10 mM D-glucose, maintained at pH 7.3 by bubbling with 95% O<sub>2</sub>/5% CO<sub>2</sub>. Slices were kept at 37°C for at least 30 min and then allowed to return to room temperature. Recordings were made 2 to 8 h after slice preparation. The sucrose-based aCSF solution used for dissection and slicing was identical with standard aCSF with the exception that NaCl was replaced by isosmotic sucrose.

**Whole-Cell Patch-Clamp Recording.** Individual cerebellar brain slices were placed in a recording chamber maintained at room temperature and superfused with carboxygenated standard aCSF. PCs were identified using an IR-DIC upright Olympus BX50WI microscope (Olympus, Tokyo, Japan) with a 60 $\times$ , 0.9 numerical aperture water immersion lens. Whole-cell patch-clamp recordings were made from PCs at a holding potential of  $-70$  mV using an EPC-9 amplifier (HEKA, Lambrecht/Pfalz, Germany) controlled by Pulse software (HEKA) using a Macintosh G4 computer (Apple Computer, Cupertino, CA). Electrodes (3–7 M $\Omega$ ) were pulled from borosilicate glass (Harvard Apparatus, Kent, United Kingdom) filled with an intracellular solution containing 140 mM CsCl, 1 mM MgCl<sub>2</sub>, 1 mM CaCl<sub>2</sub>, 10 mM EGTA, 4 mM MgATP, 0.4 mM NaGTP, and 10 mM HEPES, pH 7.3. For whole-cell recording, slow capacitance was compensated, and series resistance was typically monitored at 15 to 20 M $\Omega$  with 70 to 90% compensation. Data were sampled at 5 kHz and filtered at one-third of the sampling frequency. Spontaneous inhibitory postsynaptic currents were first recorded for a minimum of 15 min to ensure recording stability. To isolate mIPSCs, slices were treated with tetrodotoxin (TTX, 1  $\mu$ M) and NBQX (2.5  $\mu$ M). In all experiments, ligands were bath-applied for a minimum of 20 min to achieve maximal steady-state effects, and a minimum 150-s recording was used as raw data for event detection. Solvent was present at a maximum final concentration of 0.1% (v/v); solvent, applied alone at equivalent experimental concentrations, has no effect on synaptic responses in this preparation (Bardo et al., 2002).

## Data and Statistical Analysis

Data were initially exported using Pulsefit (HEKA) and then imported to AxoGraph 4.0 software for event detection (<http://axographx.com/index.html>). All electrophysiology data were analyzed using Prism 4 or Axograph 4.0 software. Cumulative frequency plots were constructed for interevent intervals using 5-ms bins. In all cases, because amplitude distributions were skewed and did not pass the D'Agostino and Pearson omnibus normality test, differences between the means of the medians were used for parametric testing. Cumulative frequency plots were analyzed using the Kolmogorov-Smirnov test. Paired Student's *t* tests were used to compare control and first treatment values. Comparison of the means from multiple treatment groups was performed using repeated measurement one-way ANOVA tests. Tukey's HSD tests were performed when a repeated-measurement one-way ANOVA yielded significant differences. Differences were con-

sidered significant if  $p < 0.05$ . All data are expressed as means  $\pm$  S.E.M.; *n* refers to the number of replicants used.

## Pharmacology

The following agents were used: AM251, CP55940, NBQX (disodium salt), WIN55 (all from Tocris Cookson, Bristol, UK); (*R*)-baclofen (Ascent Scientific, Bristol, UK); and TTX-citrate (Alomone Labs, Jerusalem, Israel). PSNCBAM-1 was kindly provided by Prosidion Limited (Oxford, United Kingdom). TTX-citrate was dissolved in distilled water, and NBQX, WIN55, PSNCBAM-1, and AM251 were dissolved in dimethyl sulfoxide. All drugs were made up as 1000 $\times$  stock solutions except for AM251 (made up as 5000 $\times$  stock) and stored at  $-20^{\circ}\text{C}$ . Drug stock solutions were diluted in carboxygenated standard aCSF immediately before application.

## Results

Previous studies have identified PSNCBAM-1 as an allosteric antagonist at recombinant human CB<sub>1</sub> receptors (Horswill et al., 2007). We first sought to extend studies to CB<sub>1</sub> receptors in native murine cerebellar membranes (Dennis et al., 2008). The CB receptor agonist CP55940 stimulated [<sup>35</sup>S]GTP $\gamma$ S binding to a maximum of  $172.0 \pm 7.3\%$  of basal ( $n = 4$ ) with a pEC<sub>50</sub> of  $8.04 \pm 0.03$  (Fig. 1A). The CB receptor agonist WIN55 also stimulated [<sup>35</sup>S]GTP $\gamma$ S binding, but with a significantly higher maximum effect ( $236.5 \pm 6.2\%$  of basal,  $n = 4$ ,  $p < 0.01$ , Student's *t* test) and a significantly less potent pEC<sub>50</sub> of  $6.22 \pm 0.10$  ( $p < 0.01$ , Student's *t* test) than seen for CP55940 (Fig. 1B). PSNCBAM-1 behaved noncompetitively against both CB receptor agonists, producing a substantial reduction in maximal [<sup>35</sup>S]GTP $\gamma$ S stimulation and only weakly affecting agonist potency. Agonist-dependent effects were also seen; for example, 1  $\mu$ M PSNCBAM-1 was sufficient to almost fully inhibit CP55940 stimulation; by contrast, 10  $\mu$ M PSNCBAM-1 was unable to fully inhibit the WIN55-induced response. We further investigated this phenomenon by determining PSNCBAM-1 potency for inhibition against a single agonist concentration that stimulated a similar amount of GTP $\gamma$ S binding. Although these experiments are dependent on the agonist concentration chosen, PSNCBAM-1 displayed significantly greater potency against CP55940 than WIN55 (pIC<sub>50</sub> of  $7.32 \pm 0.20$  and  $6.50 \pm 0.15$ , respectively;  $p < 0.05$ , Student's *t* test). Overall, these data confirm PSNCBAM-1 noncompetitive, agonist-dependent actions in [<sup>35</sup>S]GTP $\gamma$ S binding assays.

**Effects of PSNCBAM-1 on CB Receptor Agonist Modulation of Inhibitory Neurotransmission.** Having demonstrated that PSNCBAM-1 has differential agonist-dependent actions in [<sup>35</sup>S]GTP $\gamma$ S binding assays in isolated cerebellar membranes, we next examined the potential functional effects of PSNCBAM-1 on modulation of synaptic transmission at IN-PC synapses in C57BL/6 mice. We first confirmed that WIN55 exerted a comparable agonistic effect to that demonstrated previously in TO strain mice (Ma et al., 2008). Bath application of WIN55 (5  $\mu$ M) significantly decreased mean mIPSC frequency ( $73 \pm 6\%$ ,  $n = 8$ ,  $p < 0.01$ , Student's *t* test; Fig. 2A), there was no accompanying change in mean mIPSC amplitude ( $n = 8$ ;  $p = 0.52$ , Student's *t* test). CP55940 (5  $\mu$ M) also significantly decreased mean mIPSC frequency ( $64 \pm 6\%$ ,  $n = 6$ ,  $p < 0.01$ , Student's *t* test; Fig. 2B), again, with no effect



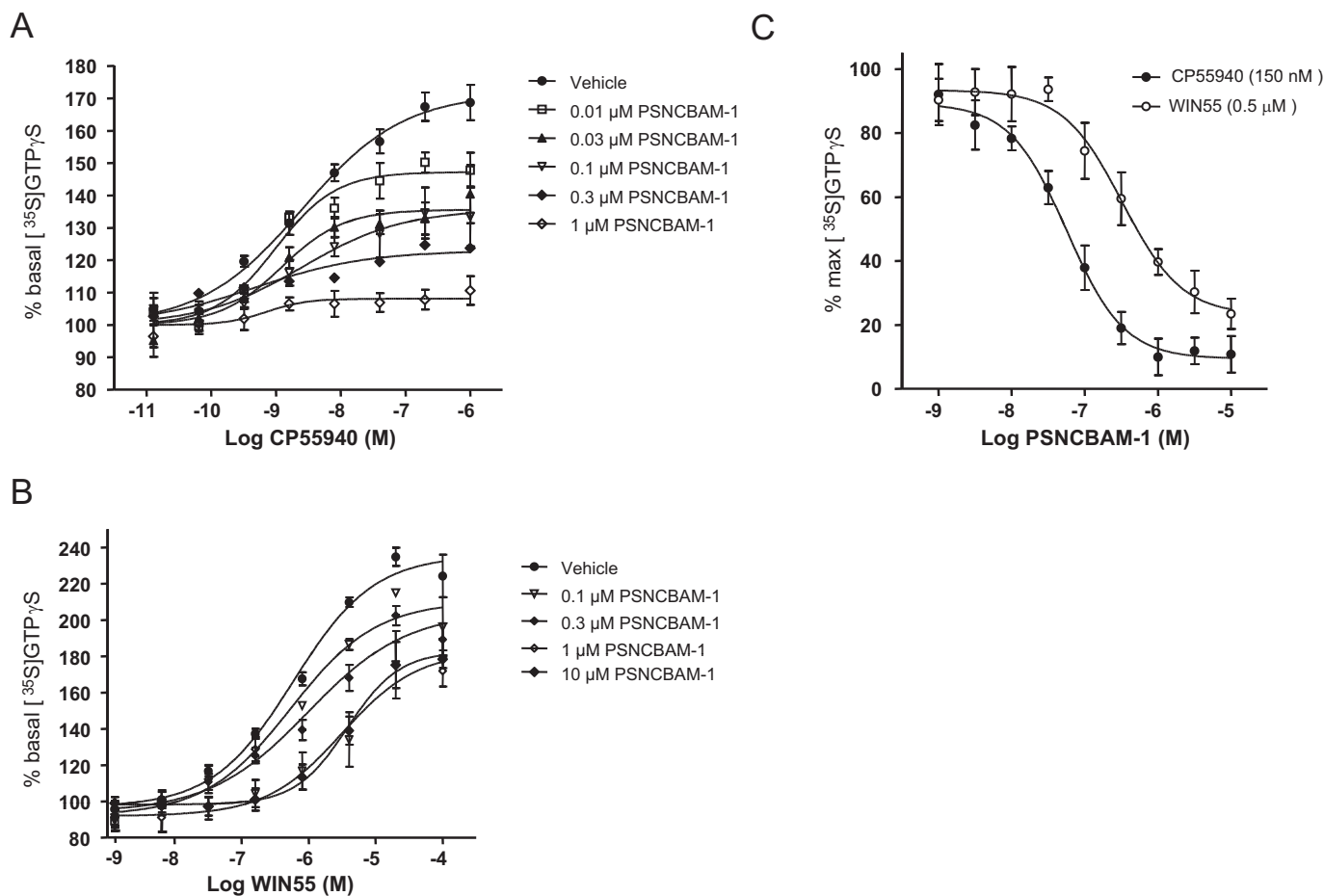
on amplitude distribution ( $n = 6$ ;  $p = 0.99$ , Student's  $t$  test). In these and all subsequent experiments, no statistically significant changes in mean mIPSC amplitude were seen, and these effects are not further discussed. Overall, these data are consistent with a reduction in presynaptic GABA release without accompanying postsynaptic changes and also confirm CB<sub>1</sub> agonist effects at IN-PC synapses (Ma et al., 2008) to be independent of the mouse strain used.

To examine the effects of PSNCBAM-1 upon CB<sub>1</sub> agonist-mediated modulation of inhibitory transmission in the cerebellum, WIN55 or CP55940 was applied in the presence of PSNCBAM-1 (Fig. 3). Pretreatment with 10  $\mu$ M PSNCBAM-1 had no significant effect on WIN55-induced inhibition of synaptic transmission, such that 5  $\mu$ M WIN55 still caused a significant decrease in mean mIPSC frequency ( $76 \pm 4\%$ ,  $n = 7$ ,  $p < 0.01$ , Student's  $t$  test; Fig. 3A). By marked contrast, PSNCBAM-1 abolished the inhibitory effect of 5  $\mu$ M CP55940 on mean mIPSC frequency ( $97 \pm 11\%$ ,  $n = 5$ ,  $p = 0.83$ , Student's  $t$  test; Fig. 3B). Together, these data demonstrate PSNCBAM-1 can cause CB receptor functional antagonism at IN-PC synapses and reflect an agonist-dependent effect.

**Effects of PSNCBAM-1 on CB<sub>1</sub> Receptor Antagonist Modulation of Inhibitory Neurotransmission.** In our previous study, we reported that the synthetic CB<sub>1</sub> antagonist/inverse agonist AM251 increased inhibitory neurotrans-

mission at IN-PC synapses in TO strain mice, as demonstrated by an increase in mean mIPSC frequency beyond control levels (Ma et al., 2008). This increase can be generally attributable to the removal of endocannabinergic tone by a CB<sub>1</sub> antagonist action or the blockade of constitutive activity by an inverse agonist action. Therefore, we next compared the actions of PSNCBAM-1 with those of AM251 at IN-PC synapses in C57BL/6 mice. PSNCBAM-1 (10  $\mu$ M) had no significant effect on mean mIPSC frequency ( $99 \pm 6\%$ ,  $n = 12$ ,  $p = 0.80$ , Student's  $t$  test; Fig. 4A). By contrast, 2  $\mu$ M AM251 caused a significant increase in mean mIPSC frequency ( $117 \pm 4\%$ ,  $n = 7$ ,  $p < 0.01$ , Student's  $t$  test; Fig. 4B). These data suggest that PSNCBAM-1 lacks the CB<sub>1</sub> neutral antagonist or inverse agonist properties associated with AM251 in this system.

To confirm these data, next we activated CB receptors with WIN55 before the application of either AM251 or PSNCBAM-1 (Fig. 5). In the first of these experiments, 5  $\mu$ M WIN55 caused a significant reduction in mean mIPSC frequency ( $74 \pm 4\%$ ,  $p < 0.01$ , Student's  $t$  test) that was reversed to beyond control level by subsequent application of 2  $\mu$ M AM251 ( $115 \pm 7\%$ ,  $n = 7$ ,  $p < 0.001$ , repeated-measurement one-way ANOVA followed by a Tukey's HSD test; Fig. 5A). By contrast, in a separate set of experiments, the 5  $\mu$ M WIN55-induced significant reduction in mean mIPSC fre-



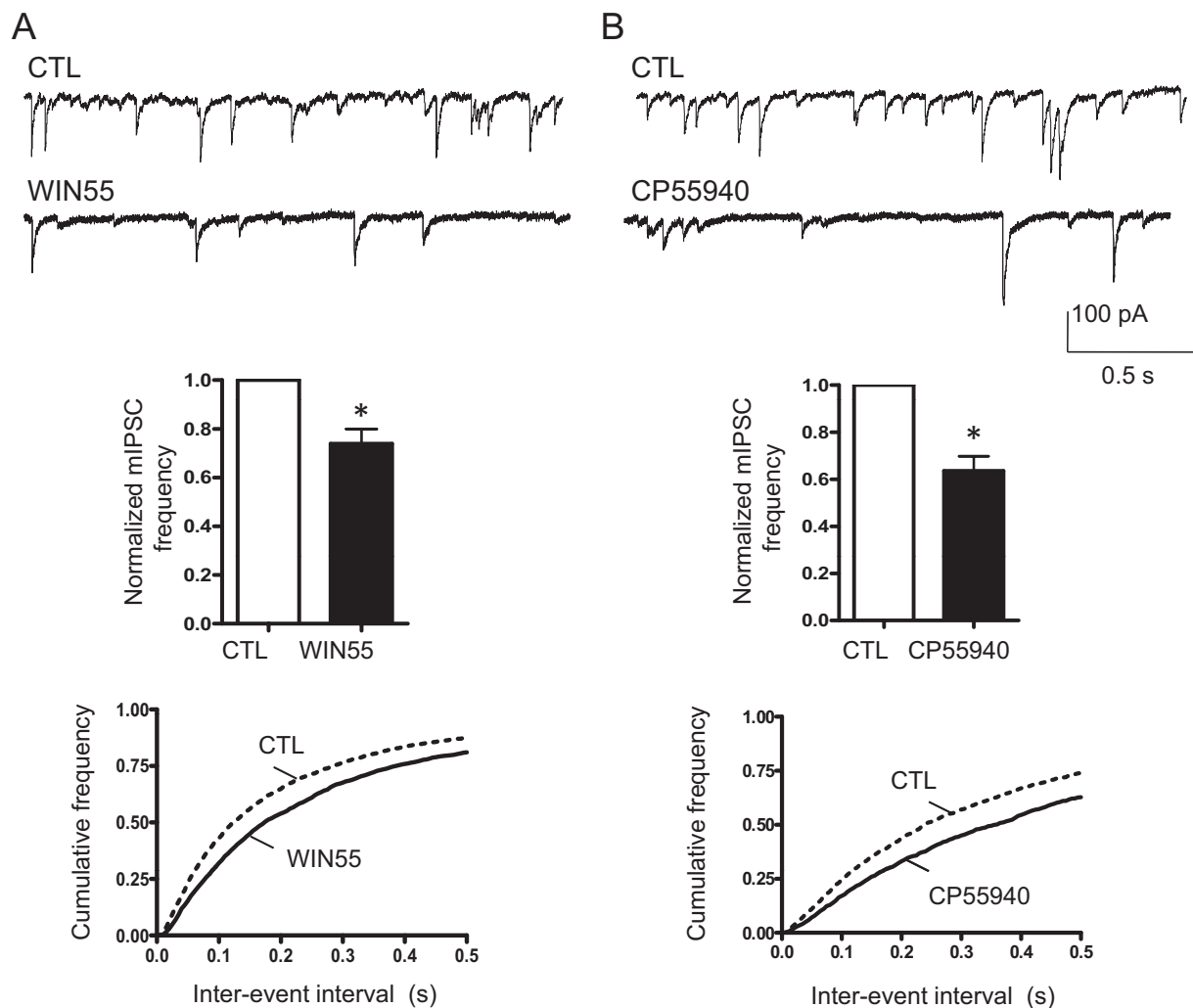
**Fig. 1.** Effects of PSNCBAM-1 on  $[^3\text{S}]\text{GTP}\gamma\text{S}$  binding in mouse cerebellar membranes. Effects of PSNCBAM-1 on log concentration-response curves for CP55940 (A) and WIN55 (B) on the percentage of basal stimulation of  $[^3\text{S}]\text{GTP}\gamma\text{S}$  binding (both mean  $\pm$  S.E.M. of four experiments). C, dose-titration effect of PSNCBAM-1 on either CP55940 (150 nM) or WIN55 (0.5  $\mu\text{M}$ ) stimulated  $[^3\text{S}]\text{GTP}\gamma\text{S}$  binding in mouse cerebellar membranes. Data points are mean  $\pm$  S.E.M. of three experiments. PSNCBAM-1 had agonist-dependent potency differences between CP55940 ( $\text{pIC}_{50} = 7.32 \pm 0.20$ ) versus WIN55 ( $\text{pIC}_{50} = 6.50 \pm 0.15$ );  $p < 0.05$ , Student's  $t$  test.

quency ( $74 \pm 6\%$ ,  $p < 0.01$ , Student's  $t$  test) was not significantly affected by  $10 \mu\text{M}$  PSNCBAM-1 ( $71 \pm 8\%$ ,  $n = 8$ ,  $p > 0.05$ , repeated-measurement one-way ANOVA followed by a Tukey's HSD test; Fig. 5B). Subsequent application of AM251 was still able to reverse WIN55 effects (mean mIPSC frequency increased to  $97 \pm 6\%$ ,  $n = 8$ ;  $p < 0.01$ , repeated-measurement one-way ANOVA followed by a Tukey's HSD test; Fig. 5B). In this experiment, mean mIPSC frequency in the presence of AM251 did not exceed control levels, suggesting that PSNCBAM-1 pretreatment can affect AM251 actions; therefore, we next examined the effects of PSNCBAM-1 application after AM251 (Fig. 6). In this set of experiments,  $2 \mu\text{M}$  AM251 caused a significant increase in mean mIPSC frequency ( $117 \pm 4\%$ ,  $n = 7$ ;  $p < 0.01$ , repeated-measurement one-way ANOVA followed by a Tukey's HSD test), which, in turn, was significantly reduced by subsequent application of  $10 \mu\text{M}$  PSNCBAM-1 ( $104 \pm 3\%$ ,  $n = 7$ ;  $p < 0.01$ , repeated-measurement one-way ANOVA followed by a Tukey's HSD test; Fig. 6). These data demonstrate that PSNCBAM-1 had actions on a  $\text{CB}_1$  antagonist/inverse agonist in addition to the agonist-dependent modulation described above.

Finally, to test for potential actions at other  $\text{G}\alpha_{i/o}$ -coupled GPCRs that modulate inhibitory transmission at IN-PC synapses, we investigated PSNCBAM-1 effects on  $\text{GABA}_\text{B}$  receptor-mediated inhibition (Harvey and Stephens, 2004). Bath application of the  $\text{GABA}_\text{B}$  agonist baclofen ( $20 \mu\text{M}$ ) significantly decreased mean mIPSC frequency ( $78 \pm 3\%$ ,  $n = 4$ ,  $p < 0.01$ , Student's  $t$  test; Fig. 7A). Pretreatment with  $10 \mu\text{M}$  PSNCBAM-1 had no significant effect on baclofen-induced inhibition of synaptic transmission, such that  $20 \mu\text{M}$  baclofen still caused a significant decrease in mean mIPSC frequency ( $72 \pm 4\%$ ,  $n = 5$ ,  $p < 0.01$ , Student's  $t$  test; Fig. 7B). Taken together, these electrophysiological data suggest that PSNCBAM-1 displays  $\text{CB}_1$  receptor ligand-dependent actions consistent with functional allosteric antagonism at cerebellar IN-PC synapses.

## Discussion

Recent studies have identified a series of Organon compounds and the structurally similar PSNCBAM-1 as  $\text{CB}_1$  receptor allosteric antagonists (Price et al., 2005; Horswill et al., 2007). Here, we demonstrate PSNCBAM-1 func-



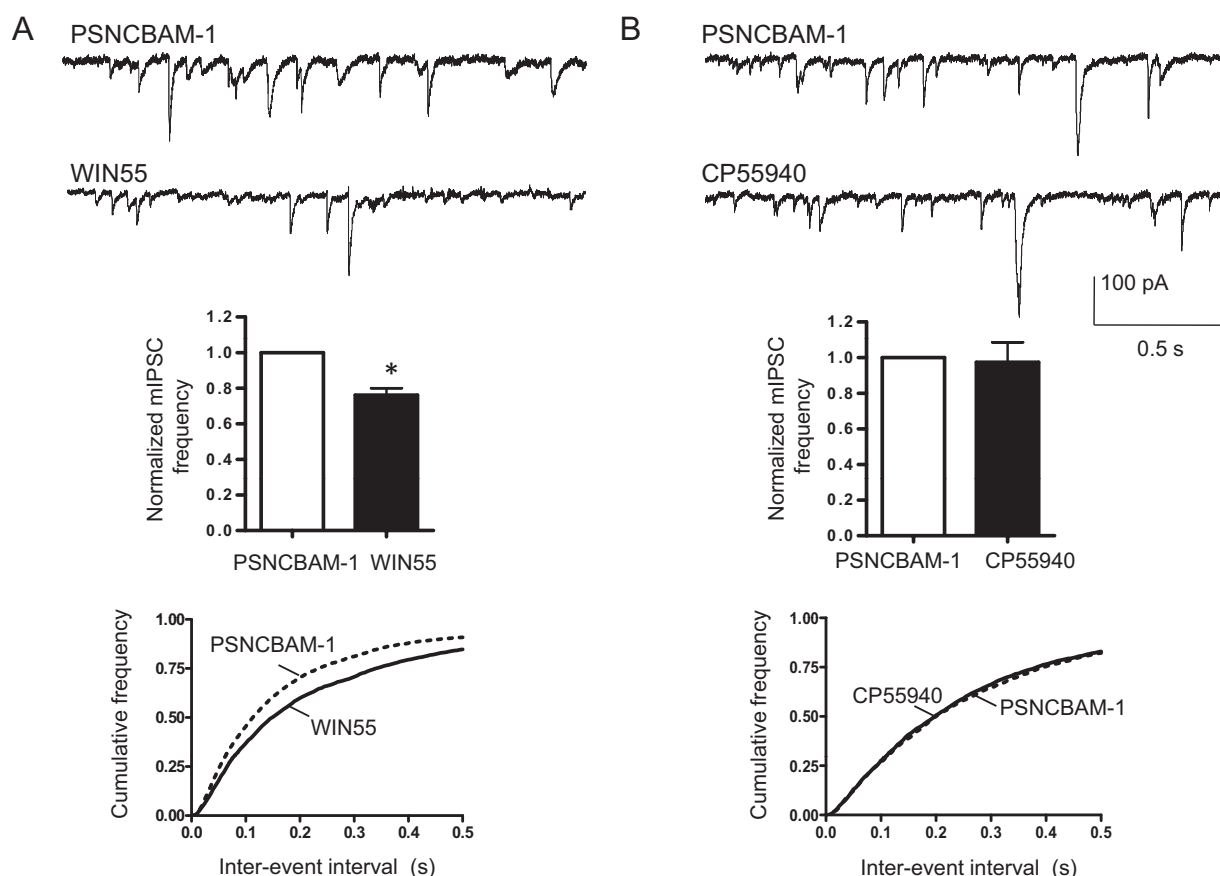
**Fig. 2.** Effects of CB agonists on inhibitory neurotransmission at IN-PC synapses. Effect of  $5 \mu\text{M}$  WIN55 ( $n = 8$ ) (A) and  $5 \mu\text{M}$  CP55940 ( $n = 6$ ) (B) on mIPSCs; example raw data traces (top), summary bar graph showing effects on normalized mIPSC frequency (middle), and cumulative frequency curves for effects on interevent interval (bottom). Both WIN55 and CP55940 significantly reduced normalized mIPSC frequency [ $^*$ ,  $p < 0.01$  versus control (CTL), Student's  $t$  test] and caused a significant rightward shift of the CTL interevent interval curve (both  $p < 0.0001$  in individual cells, Kolmogorov-Smirnov test).

tional CB<sub>1</sub> antagonism and agonist-dependent effects on [<sup>35</sup>S]GTPγS binding in native cerebellar membranes and reveal that these effects extend to CB<sub>1</sub> ligand-dependent modulation of inhibitory neurotransmission in the mammalian CNS.

**PSNCBAM-1 Displays Agonist-Dependent Potency in [<sup>35</sup>S]GTPγS Binding Assays.** PSNCBAM-1 caused a noncompetitive antagonism of CB receptor agonist-stimulated [<sup>35</sup>S]GTPγS binding in cerebellar membranes. Overall, PSNCBAM-1 achieved only a partial inhibition of WIN55-induced responses, with PSNCBAM-1 displaying higher potency for inhibition of CP55940 versus WIN55 stimulation when tested against a range of agonist concentration and in dose-titration experiments against a fixed agonist concentration. A similar differentiation was seen in human embryonic kidney 293 membranes expressing the human CB<sub>1</sub> receptor, in which PSNCBAM-1 also displayed higher potency for inhibition of agonist-stimulated [<sup>35</sup>S]GTPγS binding by CP55940 than by WIN55 (Supplemental Fig. 1). Thus, PSNCBAM-1 displays agonist-dependent potency at mouse CB<sub>1</sub> receptors in native membranes and recombinant human CB<sub>1</sub> receptors. A caveat to these data is that WIN55 may stimulate a non-CB<sub>1</sub>-mediated component of [<sup>35</sup>S]GTPγS binding (Breivogel et al., 2001). In the present study, WIN55 displayed a higher efficacy than CP55940 in stimulation of [<sup>35</sup>S]GTPγS binding in cerebellar membranes, as reported in

some previous studies (Breivogel et al., 2003; Childers, 2006). However, we have shown that WIN55-stimulated [<sup>35</sup>S]GTPγS binding in cerebellar membranes is potently blocked by the CB<sub>1</sub> antagonists AM251 and Δ<sup>9</sup>-tetrahydrocannabinavarin (Δ<sup>9</sup>-THCV) (Dennis et al., 2008), and that WIN55 inhibition at IN-PC synapses is prevented by Δ<sup>9</sup>-THCV (Ma et al., 2008), arguing against WIN55 causing functional CB<sub>1</sub>-independent effects here. With regard to alternative receptor targets, it is of interest that CP55940, but not WIN55, is a ligand at GPR55, a lysophosphatidylinoitol receptor, with some sensitivity to cannabinoids (Ross, 2009). However, in our hands, the GPR55 agonist 5-methyl-4-[(1*R*,6*R*)-3-methyl-6-(1-methylethenyl)-2-cyclohexen-1-yl]-1,3-benzenediol (O-1602) lacked effects on [<sup>35</sup>S]GTPγS binding in cerebellar membranes (I. Smith, B. J. Whalley, and G. J. Stephens, unpublished data). Moreover, it is currently unknown whether PSNCBAM-1 acts at GPR55. In the future, it will be useful to test the effects of CB<sub>1</sub> allosteric antagonists in *cnr1*(<sup>-/-</sup>) and *GPR55*(<sup>-/-</sup>) animals. Overall, PSNCBAM-1 displays both noncompetitive antagonism and agonist-dependent potency in [<sup>35</sup>S]GTPγS binding studies, characteristics associated with allosteric mechanisms (Conn et al., 2009).

**C57BL/6 Mouse IN-PC Synapses Possess Functional CB<sub>1</sub> Receptors.** Activation of CB<sub>1</sub> receptors at IN-PC synapses attenuates inhibitory neurotransmission, resulting in consequential synaptic disinhibition of PC output (Ma et al.,

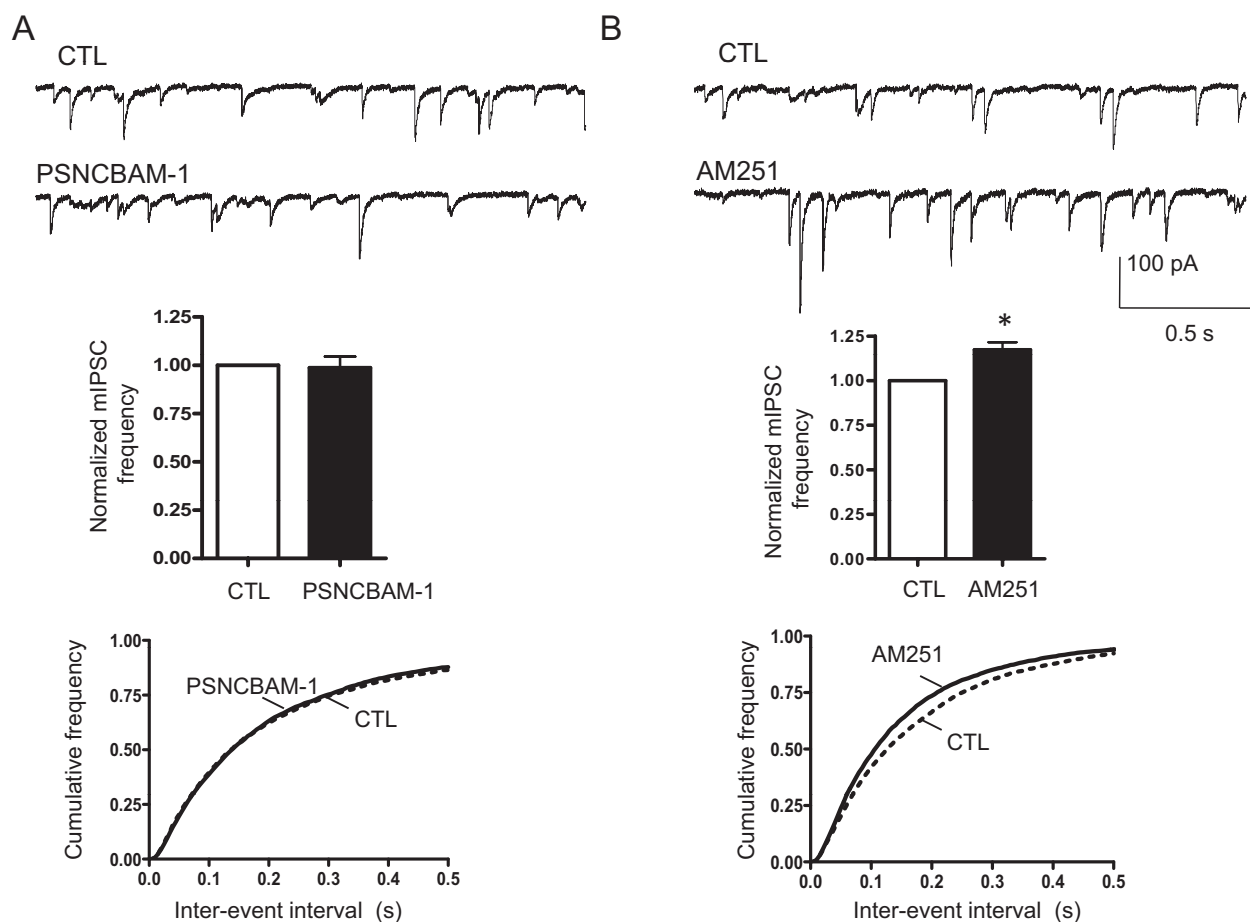


**Fig. 3.** Effect of pretreatment with PSNCBAM-1 on CB agonists. Effect of 10 μM PSNCBAM-1 on 5 μM WIN55 (*n* = 7) (A) and 5 μM CP55940 (*n* = 5) (B) actions on mIPSCs; example raw data traces (top), summary bar graph showing effects on normalized mIPSC frequency (middle), cumulative frequency curves for effects on interevent interval (bottom). PSNCBAM-1 had agonist-dependent potency differences, blocking CP55940 effects, but lacking action on WIN55 effects, such that the WIN55-mediated significant reduction in normalized mIPSC frequency [*p* < 0.01 versus control (CTL), Student's *t* test] and significant rightward shift of the CTL interevent interval curve (*p* < 0.0001 in individual cells, Kolmogorov-Smirnov test) were sustained.

2008). Here, both WIN55 and CP55940 caused a significant decrease in mIPSC frequency but produced no change in mIPSC amplitude, consistent with CB<sub>1</sub> agonist-mediated presynaptic inhibition of GABA release. We chose to record mIPSCs not only to isolate presynaptic events but also to negate any potentially confounding WIN55-mediated effect on Ca<sup>2+</sup> channels, which has been proposed to underlie WIN55 CB<sub>1</sub> receptor-independent effects on synaptic transmission (Németh et al., 2008) and postsynaptic PC output (Fisyunov et al., 2006). Because miniature, action potential-independent events at IN-PC synapses occur independently of Ca<sup>2+</sup> influx into the axon terminal via voltage-dependent Ca<sup>2+</sup> channels (Harvey and Stephens, 2004; Stephens, 2009), it is unlikely that such a mechanism could account for the observed WIN55-induced reduction in inhibitory transmission. Consequently, we propose that the CB<sub>1</sub> pathway-mediated responses seen here occurs downstream of Ca<sup>2+</sup> entry, involves the release machinery, and results in the inhibition of exocytosis of GABA-containing vesicles. We also demonstrate that AM251 increases inhibitory neurotransmission. Together, these results confirm functional presynaptic CB<sub>1</sub> receptors at IN-PC synapses in C57BL/6 mice, thereby validating the preparation for the study of functional PSNCBAM-1 effects.

**PSNCBAM-1 Displays Agonist-Dependent Potency in Electrophysiological Studies.** PSNCBAM-1 pretreatment blocked CP55940-induced inhibition of synaptic transmission; by contrast, PSNCBAM-1 had no effect upon WIN55-induced inhibition. Thus, PSNCBAM-1 possesses an agonist-dependent functional antagonism at IN-PC synapses. This agonist-dependence is in agreement with our [<sup>35</sup>S]GTPγS binding assays and data from yeast reporter assays by Horswill et al. (2007) that showed PSNCBAM-1 more potently antagonized the stimulation of CB<sub>1</sub> receptors by CP55940 than by WIN55.

Here, PSNCBAM-1 had no effect on inhibitory neurotransmission when applied alone; by contrast, the CB<sub>1</sub> antagonist/inverse agonist AM251 increased mIPSC frequency. We have shown previously that AM251, Δ<sup>9</sup>-THCV, and SR141716A all increase inhibitory neurotransmission at IN-PC synapses, an effect consistent with a blockade of endocannabinergic tone or abolition of constitutive CB<sub>1</sub> activity (Ma et al., 2008). Moreover, pharmacological actions of PSNCBAM-1 exhibit assay-dependence, behaving as a noncompetitive antagonist in an in vivo feeding model and CB<sub>1</sub> yeast reporter, GTPγS, and cAMP assays but demonstrating partial inverse agonism against basal [<sup>35</sup>S]GTPγS binding (Horswill et al., 2007). Here, PSNCBAM-1 lacked the intrinsic activity associated



**Fig. 4.** Effect of PSNCBAM-1 and AM251 on inhibitory neurotransmission at IN-PC synapses. Effect of 10  $\mu$ M PSNCBAM-1 ( $n = 12$ ) (A) and 2  $\mu$ M AM251 ( $n = 7$ ) on mIPSCs (B); example raw data traces (top), summary bar graph showing effects on normalized mIPSC frequency (middle), and cumulative frequency curves for effects on interevent interval (bottom). PSNCBAM-1 lacked effects on mIPSCs; AM251 significantly increased mean normalized mIPSC frequency [ $^*$ ,  $p < 0.01$  versus control (CTL), Student's  $t$  test] and caused a significant leftward shift of the CTL interevent interval curve ( $p < 0.0001$  in individual cells, Kolmogorov-Smirnov test).

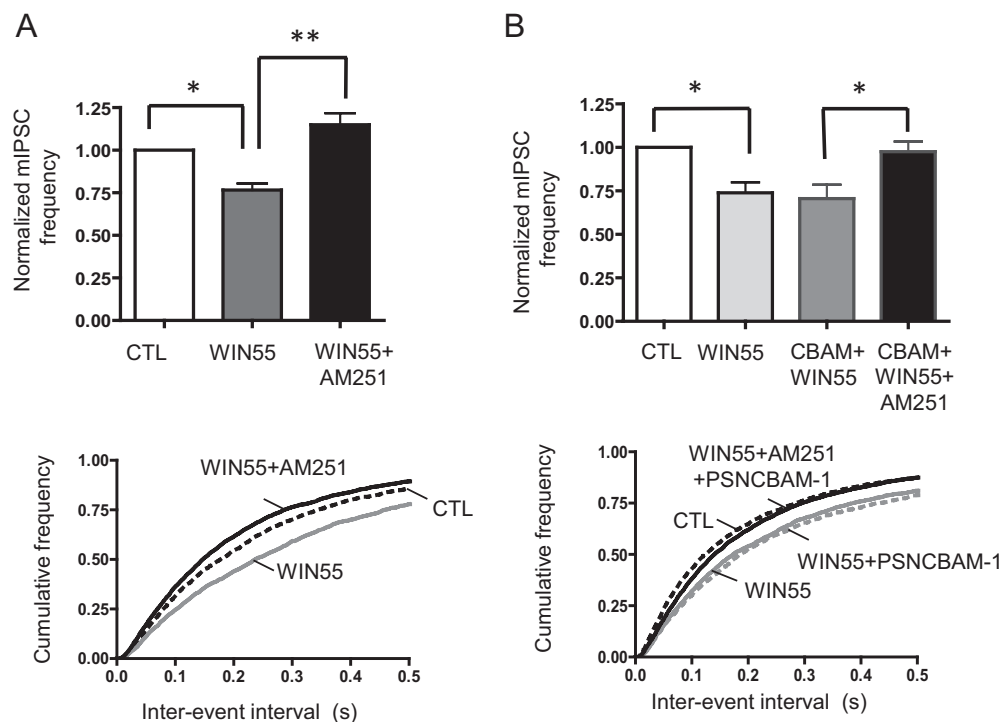


with CB<sub>1</sub> antagonists/inverse agonists at IN-PC synapses. We have proposed that AM251 acts to displace endocannabinoids at IN-PC synapses (Stephens, 2009), the lack of intrinsic PSNCBAM-1 effects further suggests that PSNCBAM-1 binds at a site distinct from that occupied by endocannabinoids. It is noteworthy that PSNCBAM-1 modulated the actions of AM251. Thus, PSNCBAM-1 attenuated the AM251-induced reversal of WIN55-induced inhibition and also reversed AM251-induced increases in inhibitory neurotransmission. These data are the first to describe PSNCBAM-1 functional effects on CB<sub>1</sub> antagonists/inverse agonists and suggest further mechanisms of CB<sub>1</sub> receptor allosteric modulation.

#### Mechanisms of PSNCBAM-1 Allosteric Antagonism.

We demonstrate that PSNCBAM-1 has distinct effects on the actions of the CB agonist CP55940 versus WIN55 and also modulates the actions of the CB<sub>1</sub> antagonist/inverse agonist AM251. A parsimonious explanation of our data is that PSNCBAM-1 can bind to a CB<sub>1</sub> receptor allosteric site to exert a ligand-dependent antagonist action. Here, allosteric-orthosteric ligand interactions could also be dependent on the presence of different CB<sub>1</sub> orthosteric binding sites for distinct ligands. In this regard, molecular modeling studies have shown that CP55940 (a synthetic derivative of  $\Delta^9$ -tetrahydrocannabinol) and WIN55 (an aminoalkylindole) bind at distinct CB<sub>1</sub> binding sites (McAllister et al., 2003, 2004), in agreement with earlier mutagenesis studies (Song and Bonner, 1996). Thus, PSNCBAM-1 allosteric binding may selec-

tively affect different CB<sub>1</sub> orthosteric sites. The phenomenon whereby certain allosteric agents can interact with one class of ligands, but not another, has been termed "probe-dependence" and is likely to be conserved across GPCR classes (Leach et al., 2007; May et al., 2007; Kenakin, 2008). In the classic ternary complex model for receptor allostery (Ehlert, 1988), binding to an allosteric site alters ligand affinity for the orthosteric site in either a positive, negative, or neutral direction. PSNCBAM-1 had positive cooperativity for agonist [<sup>3</sup>H]CP55940 binding but negative cooperativity for antagonist/inverse agonist [<sup>3</sup>H]SR141716A binding in competition experiments (Horswill et al., 2007). Comparable effects were reported for Organon CB<sub>1</sub> allosteric antagonists (Price et al., 2005). Thus, CB<sub>1</sub> allosteric antagonists exhibit ligand-dependent actions on orthosteric affinity (Ross, 2007a,b). Moreover, in a manner that is presently unique to CB<sub>1</sub> allosteric antagonists, changes in orthosteric efficacy are reported to occur in a direction opposite to those on orthosteric affinity, with these compounds causing noncompetitive antagonism of CB<sub>1</sub> receptor function. It may be hypothesized that interference with G proteins or G protein coupling may explain why CB<sub>1</sub> allosteric antagonists enhance CP55940 receptor binding but inhibit CP55940 functional effects. However, it has been reported previously that PSNCBAM-1 lacks effects on CB<sub>2</sub> receptors, the closest homolog to CB<sub>1</sub> (Horswill et al., 2007), and here we demonstrate that PSNCBAM-1 lacked modulatory effects on GABA<sub>B</sub> receptor pathways at IN-PC synapses. Together with



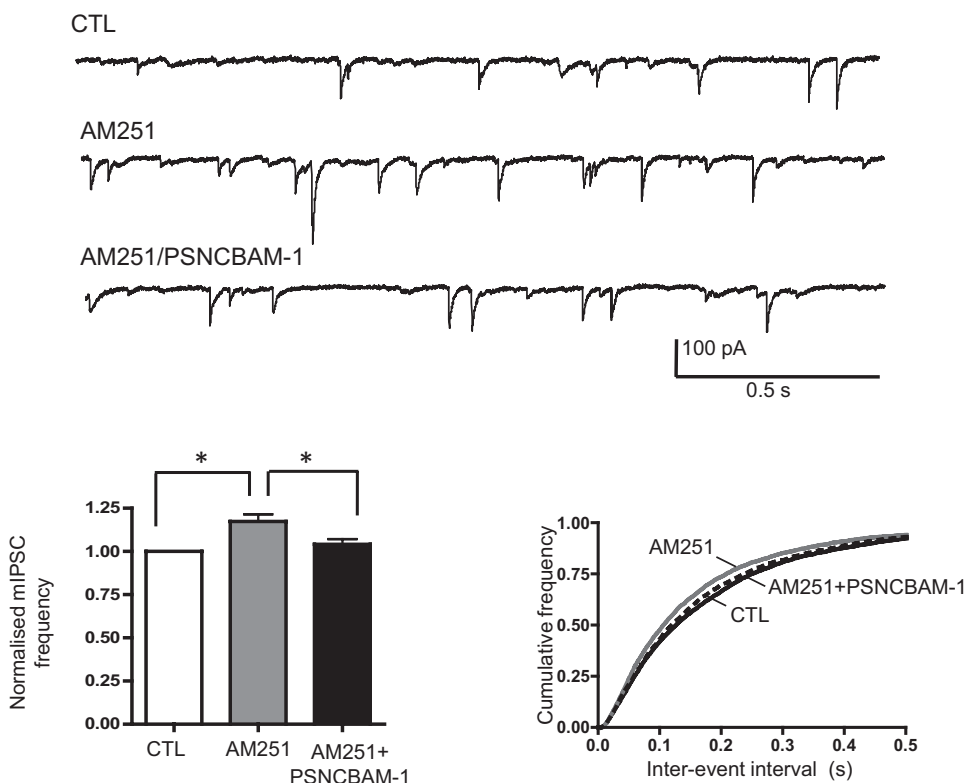
**Fig. 5.** Effect of PSNCBAM-1 and AM251 on WIN55 actions. A, effect of 5  $\mu$ M WIN55 and subsequent application of 2  $\mu$ M AM251 ( $n = 7$ ) on mIPSCs; summary bar graph showing effects on normalized mIPSC frequency (top), and cumulative frequency curves for effects on interevent interval (bottom). WIN55 caused a reduction in normalized mIPSC frequency (\*,  $p < 0.01$ , Student's  $t$  test), which was reversed beyond control (CTL) levels by AM251 (\*\*,  $p < 0.001$ , repeated-measurement one-way ANOVA followed by a Tukey's HSD test). These data were reflected by significant shifts of the CTL interevent interval curve for each treatment (both  $p < 0.0001$  in individual cells; Kolmogorov-Smirnov test). B, effect of 5  $\mu$ M WIN55 and subsequent applications of 10  $\mu$ M PSNCBAM-1 and then 2  $\mu$ M AM251 ( $n = 8$ ) on mIPSCs; summary bar graph showing effects on normalized mIPSC frequency (top), and cumulative frequency curves for effects on interevent interval (bottom). WIN55 caused a reduction in normalized mIPSC frequency (\*,  $p < 0.01$ , Student's  $t$  test), which was not affected by PSNCBAM-1 but was increased by AM251 (\*,  $p < 0.01$ , repeated-measurement one-way ANOVA followed by a Tukey's HSD test). These data were reflected by significant shifts of the interevent interval curve for WIN55 and AM251 treatment (both  $p < 0.0001$  in individual cells; Kolmogorov-Smirnov test) but a lack of effect of PSNCBAM-1.



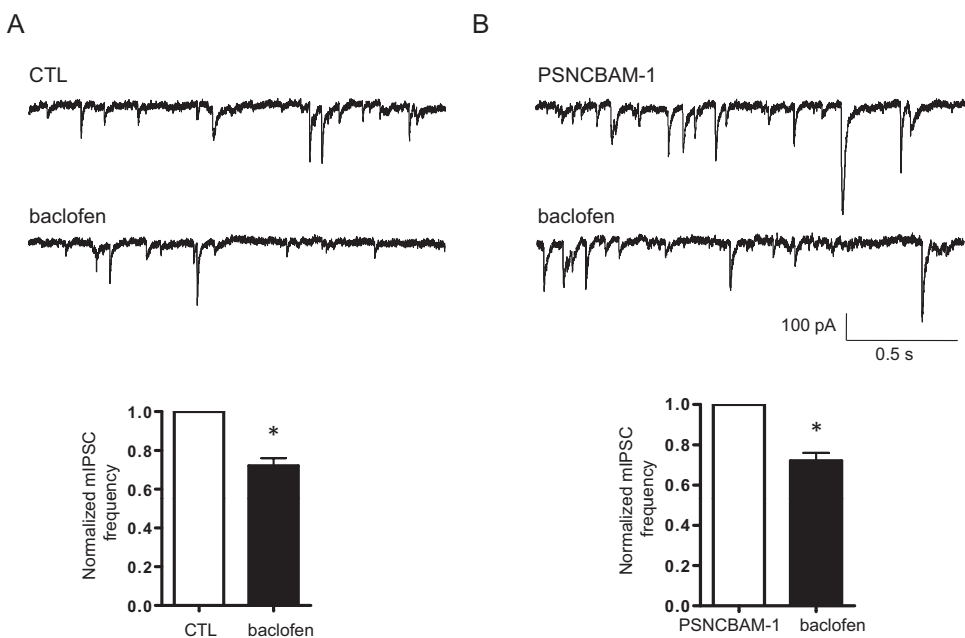
the differential effects on CB<sub>1</sub> ligands, these data suggest a lack of "nonselective" PSNCBAM-1 actions on G proteins or their coupling.

Overall, our data are consistent with PSNCBAM-1 binding to a CB<sub>1</sub> receptor allosteric site, leading to a reduction of receptor function efficacy for both CP55940 and AM251. These data extend demonstrations of reduced receptor function by CB<sub>1</sub> allosteric antagonists to functional assays of neuronal excitability and show that PSNCBAM-1 differentially affects CB<sub>1</sub> ligand-mediated modulation of inhibitory neurotransmission.

**Therapeutic Potential of CB<sub>1</sub> Allosteric Antagonism.** CB<sub>1</sub> receptor activation by exogenous agents (e.g.,  $\Delta^9$ -tetrahydrocannabinol) results in severe motor incoordination and associated cerebellar dysfunction (DeSanty and Dar, 2001; Patel and Hillard, 2001). Therefore, blockade of CB<sub>1</sub> receptors could offer a viable therapeutic strategy in diseases such as cerebellar ataxia. A variety of therapeutic advantages of GPCR allosteric modulators have been described. First, GPCR allosteric binding sites show divergence (Christopoulos, 2002), which could be exploited to reduce side effects (Jensen and Spalding, 2004). Second, allosteric modu-



**Fig. 6.** Effect of PSNCBAM-1 on AM251. Effect of 2  $\mu$ M AM251 and subsequent application of 10  $\mu$ M PSNCBAM-1 ( $n = 7$ ) on mIPSCs; example raw data traces (top), summary bar graph showing effects on normalized mIPSC frequency (bottom left), and cumulative frequency curves for effects on interevent interval (bottom right). AM251 caused an increase in mean normalized mIPSC frequency (\*,  $p < 0.01$ , Student's  $t$  test), which was reversed to control (CTL) levels by PSNCBAM-1 (\*,  $p < 0.01$ , repeated-measurement one-way ANOVA followed by a Tukey's HSD test). These data were reflected by significant shifts of the interevent interval curve for each treatment (both  $p < 0.0001$  in individual cells, Kolmogorov-Smirnov test).



**Fig. 7.** Effect of pretreatment with PSNCBAM-1 on GABA<sub>B</sub>-mediated inhibition at IN-PC synapses. Effect of 20  $\mu$ M baclofen on control mIPSCs ( $n = 4$ ) (A) and in the presence of 10  $\mu$ M PSNCBAM-1 ( $n = 5$ ) (B); example raw data traces (top), and summary bar graph showing effects on normalized mIPSC frequency (bottom). PSNCBAM-1 had no effect on baclofen action, such that a baclofen-mediated significant reduction in normalized mIPSC frequency was seen under both conditions (\*,  $p < 0.01$ , Student's  $t$  test).

lators may produce effects irrespective of dose, reducing the potential for toxicity (May and Christopoulos, 2003). For example, no adverse or toxic effects were seen after long-term PSNCBAM-1 administration in vivo (Horswill et al., 2007). Finally, allosteric antagonists can lack the intrinsic effects in the absence of an orthosteric ligand, allowing selective tuning of drug effects (Birdsall et al., 1996; Christopoulos and Kenakin, 2002). Here, PSNCBAM-1 lacked intrinsic activity at IN-PC synapses; by contrast, CB<sub>1</sub> antagonists/inverse agonists increase inhibitory transmission (Ma et al., 2008). Intrinsic changes to neuronal excitability may be undesirable; for example, the withdrawal of rimonabant as an antiobesity agent was proposed to reflect constitutive CB<sub>1</sub> activation as a result of inverse agonist actions (Jones, 2008). Thus, PSNCBAM-1 acting at an allosteric binding site has potential to reduce CNS side effects associated with orthosteric CB<sub>1</sub> antagonist/inverse agonists.

Overall, we demonstrate PSNCBAM-1 actions consistent with noncompetitive, agonist-dependent allosteric antagonism of cerebellar CB<sub>1</sub> receptors. These data extend PSNCBAM-1 functional effects to CB<sub>1</sub> ligand modulation of inhibitory neurotransmission and suggest alternative pharmacological approaches to the therapeutic modulation of neuronal excitability in the CNS.

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#### Authorship Contributions

*Participated in research design:* Wang, Horswill, Whalley, and Stephens.

*Conducted experiments:* Wang and Horswill.

*Contributed new reagents or analytic tools:* Horswill.

*Performed data analysis:* Wang and Horswill.

*Wrote or contributed to the writing of the manuscript:* Wang, Horswill, Whalley, and Stephens.

*Other:* Whalley and Stephens acquired funding for the research.

#### References

- Bardo S, Robertson B, and Stephens GJ (2002) Presynaptic internal Ca<sup>2+</sup> stores contribute to inhibitory neurotransmitter release onto mouse cerebellar Purkinje cells. *Br J Pharmacol* **137**:529–537.
- Birdsall NJ, Lazareno S, and Matsui H (1996) Allosteric regulation of muscarinic receptors. *Prog Brain Res* **109**:147–151.
- Breivogel CS, Griffin G, Di Marzo V, and Martin BR (2001) Evidence for a new G protein-coupled cannabinoid receptor in mouse brain. *Mol Pharmacol* **60**:155–163.
- Breivogel CS, Scates SM, Beletskaya IO, Lowery OB, Aceto MD, and Martin BR (2003) The effects of Δ<sup>9</sup>-tetrahydrocannabinol physical dependence on brain cannabinoid receptor. *Eur J Pharmacol* **459**:139–150.
- Childers SR (2006) Activation of G-proteins in brain by endogenous and exogenous cannabinoids. *AAPS J* **8**:E112–E117.
- Christopoulos A (2002) Allosteric binding sites on cell-surface receptors: novel targets for drug discovery. *Nat Rev Drug Discov* **1**:198–210.
- Christopoulos A and Kenakin T (2002) G protein-coupled receptor allostery and complexing. *Pharmacol Rev* **54**:323–374.
- Conn PJ, Christopoulos A, and Lindsley CW (2009) Allosteric modulators of GPCRs: a novel approach for the treatment of CNS disorders. *Nat Rev Drug Discov* **8**:41–54.
- Dennis I, Whalley BJ, and Stephens GJ (2008) Effects of Δ<sup>9</sup>-tetrahydrocannabinol on [<sup>35</sup>S]GTPγS binding in mouse brain cerebellum and piriform cortex membranes. *Br J Pharmacol* **154**:1349–1358.
- DeSanty KP and Dar MS (2001) Cannabinoid-induced motor incoordination through the cerebellar CB<sub>1</sub> receptor in mice. *Pharmacol Biochem Behav* **69**:251–259.
- Diana MA, Levenes C, Mackie K, and Marty A (2002) Short-term retrograde inhibition of GABAergic synaptic currents in rat Purkinje cells is mediated by endogenous cannabinoids. *J Neurosci* **22**:200–208.
- Diana MA and Marty A (2003) Characterization of depolarization-induced suppression of inhibition using paired interneuron–Purkinje cell recordings. *J Neurosci* **23**:5906–5918.
- Ehlert FJ (1988) Estimation of the affinities of allosteric ligands using radioligand binding and pharmacological null methods. *Mol Pharmacol* **33**:187–194.
- Fisyunov A, Tsintsadze V, Min R, Burnashev N, and Lozovaya N (2006) Cannabinoids modulate the P-type high-voltage-activated calcium currents in purkinje neurons. *J Neurophysiol* **96**:1267–1277.
- Harvey VL and Stephens GJ (2004) Mechanism of GABA receptor-mediated inhibition of spontaneous GABA release onto cerebellar Purkinje cells. *Eur J Neurosci* **20**:684–700.
- Horswill JG, Bali U, Shaaban S, Keily JF, Jeevaratnam P, Babbs AJ, Reynet C, and Wong Kai In P (2007) PSNCBAM-1, a novel allosteric antagonist at cannabinoid CB<sub>1</sub> receptors with hypophagic effects in rats. *Br J Pharmacol* **152**:805–814.
- Jensen AA and Spalding TA (2004) Allosteric modulation of G-protein coupled receptors. *Eur J Pharm Sci* **21**:407–420.
- Jones D (2008) End of the line for cannabinoid receptor 1 as an anti-obesity target? *Nat Rev Drug Discov* **7**:961–962.
- Kawamura Y, Fukaya M, Maejima T, Yoshida T, Miura E, Watanabe M, Ohno-Shosaku T, and Kano M (2006) The CB<sub>1</sub> cannabinoid receptor is the major cannabinoid receptor at excitatory presynaptic sites in the hippocampus and cerebellum. *J Neurosci* **26**:2991–3001.
- Kelm MK, Criswell HE, and Breese GR (2008) The role of protein kinase A in the ethanol-induced increase in spontaneous GABA release onto cerebellar Purkinje neurons. *J Neurophysiol* **100**:3417–3428.
- Kenakin T (2008) Functional selectivity in GPCR modulator screening. *Comb Chem High Throughput Screen* **11**:337–343.
- Leach K, Sexton PM, and Christopoulos A (2007) Allosteric GPCR modulators: taking advantage of permissive receptor pharmacology. *Trends Pharmacol Sci* **28**:382–389.
- Llano I, Leresche N, and Marty A (1991) Calcium entry increases the sensitivity of cerebellar Purkinje cells to applied GABA and decreases inhibitory synaptic currents. *Neuron* **6**:565–574.
- Ma YL, Weston SE, Whalley BJ, and Stephens GJ (2008) The phytocannabinoid Δ<sup>9</sup>-tetrahydrocannabinol modulates inhibitory neurotransmission in the cerebellum. *Br J Pharmacol* **154**:204–215.
- May LT, Avlani VA, Sexton PM, and Christopoulos A (2004) Allosteric modulation of G protein-coupled receptors. *Curr Pharm Des* **10**:2003–2013.
- May LT and Christopoulos A (2003) Allosteric modulators of G-protein-coupled receptors. *Curr Opin Pharmacol* **3**:551–556.
- May LT, Leach K, Sexton PM, and Christopoulos A (2007) Allosteric modulation of G protein-coupled receptors. *Annu Rev Pharmacol Toxicol* **47**:1–51.
- McAllister SD, Hurst DP, Barnett-Norris J, Lynch D, Reggio PH, and Abood ME (2004) Structural mimicry in class A G protein-coupled receptor rotamer toggle switches: the importance of the F3.36(201)/W6.48(357) interaction in cannabinoid CB<sub>1</sub> receptor activation. *J Biol Chem* **279**:48024–48037.
- McAllister SD, Rizvi G, Anavi-Goffer S, Hurst DP, Barnett-Norris J, Lynch DL, Reggio PH, and Abood ME (2003) An aromatic microdomain at the cannabinoid CB<sub>1</sub> receptor constitutes an agonist/inverse agonist binding region. *J Med Chem* **46**:5139–5152.
- Németh B, Ledent C, Freund TF, and Hájós N (2008) CB<sub>1</sub> receptor-dependent and -independent inhibition of excitatory postsynaptic currents in the hippocampus by WIN 55,212-2. *Neuropharmacology* **54**:51–57.
- Patel S and Hillard CJ (2001) Cannabinoid CB<sub>1</sub> receptor agonists produce cerebellar dysfunction in mice. *J Pharmacol Exp Ther* **297**:629–637.
- Price MR, Baillie GL, Thomas A, Stevenson LA, Easson M, Goodwin R, McLean A, McIntosh L, Goodwin G, Walker G, et al. (2005) Allosteric modulation of the cannabinoid CB<sub>1</sub> receptor. *Mol Pharmacol* **68**:1484–1495.
- Ross RA (2007a) Allostery and cannabinoid CB<sub>1</sub> receptors: the shape of things to come. *Trends Pharmacol Sci* **28**:567–572.
- Ross RA (2007b) Tuning the endocannabinoid system: allosteric modulators of the CB<sub>1</sub> receptor. *Br J Pharmacol* **152**:565–566.
- Ross RA (2009) The enigmatic pharmacology of GPR55. *Trends Pharmacol Sci* **30**:156–163.
- Song ZH and Bonner TI (1996) A lysine residue of the cannabinoid receptor is critical for receptor recognition by several agonists but not WIN55212-2. *Mol Pharmacol* **49**:891–896.
- Stephens GJ (2009) G-protein-coupled-receptor-mediated presynaptic inhibition in the cerebellum. *Trends Pharmacol Sci* **30**:421–430.
- Takahashi KA and Linden DJ (2000) Cannabinoid receptor modulation of synapses received by cerebellar Purkinje cells. *J Neurophysiol* **83**:1167–1180.
- Yamasaki M, Hashimoto K, and Kano M (2006) Miniature synaptic events elicited by presynaptic Ca<sup>2+</sup> rise are selectively suppressed by cannabinoid receptor activation in cerebellar Purkinje cells. *J Neurosci* **26**:86–95.

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