CB₁ Receptor Allosteric Modulators Display Both Agonist and Signaling Pathway Specificity

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ABSTRACT

We have previously identified allosteric modulators of the cannabinoid CB₁ receptor (Org 27569, PSNCBAM-1) that display a contradictory pharmacological profile: increasing the specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a decrease in CB₁ receptor agonist efficacy. Here we investigated the effect one or both compounds in a broad range of signaling endpoints linked to CB₁ receptor activation. We assessed the effect of these compounds on CB₁ receptor agonist-induced [³⁵S]GTPγS binding, simulation (Gαi-mediated), and inhibition (Gαs-mediated) of cAMP production and β-arrestin recruitment. In contrast, it acts as an enhancer of agonist-induced ERK phosphorylation. Alone, the compound can act also as an allosteric agonist, increasing cAMP production and ERK phosphorylation. We find that in both saturation and kinetic-binding experiments, the Org 27569 and PSNCBAM-1 appeared to influence only orthosteric ligand maximum occupancy rather than affinity. The data indicate that the allosteric modulators share a common mechanism whereby they increase available high-affinity CB₁ agonist binding sites. The receptor conformation stabilized by the allosterics appears to induce signaling and also selectively traffics orthosteric agonist signaling via the ERK phosphorylation pathway.

Introduction

The endocannabinoid system encompasses a family of endogenous ligands, prominent examples including anandamide and 2-arachidonoyl glycerol (2-AG), both of which are synthesized on demand and are rapidly hydrolyzed by the enzymes. Within the brain, the distribution of CB₁ receptors is heterogeneous; they are found predominantly on nerve terminals where they attenuate neurotransmitter release. CB₁ receptor–competitive antagonists-inverse agonists were developed for the treatment of obesity and nicotine addiction but were withdrawn due to associated serious psychiatric side effects (Nathan et al., 2011).

In 2005 we identified the first allosteric modulators of the cannabinoid CB₁ receptor (Price et al., 2005; Ross, 2007), followed by a structurally-related compound, 1-(4-chlorophenyl)-3-[3-(6-pyrrolidin-1-ylpyridin-2-yl)phenyl]urea (PSNCBAM-1) (Horswill et al., 2007). These compounds modulate electrically evoked contractions in the mouse vas deferens (Price et al., 2005), affect CB₁ ligand modulation of synaptic transmission (Wang et al., 2011) and have hypophagic effects in vivo (Horswill et al., 2007). They display a contradictory pharmacological profile: increasing the specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor specific binding of the CB₁ receptor agonist [³H]CP55940 but producing a concentration-related decrease in CB₁ receptor.
agonist efficacy. The molecular mechanisms underlying this paradoxical pharmacological profile remain to be fully elucidated.

CB₁ receptors are coupled to the G_{i/o} family of G proteins. Activation of these receptors leads to inhibition of adenyl cyclases, and to phosphorylation and activation of mitogen-activated protein kinases (MAPK), including extracellular signal-regulated kinases 1/2 (ERK1/2) (Turu and Hunyady, 2010). Following activation, β-arrestin molecules associate with phosphorylated CB₁ receptors. It is now accepted that a single receptor may engage different signaling pathways and that various ligands might influence these pathways differentially (Galandrin et al., 2007). This relatively new concept is termed “functional selectivity” (Baker and Hill, 2007; Renäkin, 2007) and has been described for the CB₁ receptor (Glass and Northup, 1999; Mukhopadhyay and Howlett, 2001; Anavi-Goffer et al., 2007). This term can also be applied to allosteric modulators. If it is supposed that numerous “active” receptor conformations (leading to specific signaling outcomes) can be triggered by orthostERIC agonists, then one might also postulate that any, but not always all, of these activation states may be stabilized by allosteric ligands (Hall, 2000). Allosteric ligands produce a distinctive receptor conformation which will possess a unique profile of pharmacology.

Recently, Ahn et al. (2012) provided evidence that Org 27569 may behave as a CB₁ receptor–biased ligand: acting as an allosteric agonist to induce receptor internalization and ERK phosphorylation in a G_{i/o} protein–independent manner [pertussis toxin (PTX)-insensitive] while also acting as negative allosteric modulator of CB₁ agonist–mediated guanosine 5′-O-[32P]thiotriophosphate ([32P]GTPγS) binding. Here we investigated the effects of allosteric modulators using a broad range of signaling endpoints linked to CB₁ and kinetic binding experiments in brain membranes and hCB₁-expressing cells, both allosteric modulators appeared to influence only orthosteric ligand maximum occupancy rather than affinity.

### Materials and Methods

#### Chinese Hamster Ovary hCB₁R Cells

Chinese hamster ovary (CHO) cells stably transfected with cDNA encoding human cannabinoid CB₁ receptors (see Ross et al., 1999) were maintained in Dulbecco’s modified Eagle’s medium (DMEM)–nutrient mixture F-12 Ham, supplemented with 2 mM L-glutamine, 10% fetal bovine serum, 50 IU/ml penicillin, 50 μg/ml streptomycin, Tris buffer, and Triton X-100. All cells were maintained at 37°C and 5% CO₂ in their respective media and were passage twice a week using nonenzymatic cell dissociation solution. The hCB₁-expressing cells, both allosteric modulators appeared to influence only orthosteric ligand maximum occupancy rather than affinity.

#### Human Embryonic Kidney 293-hCB₁R Cells

Untransfected human embryonic kidney (HEK293) Flp-In T-REx cells were cultured in the following growth medium: DMEM containing 4.5g/l glucose, 1 mM L-glutamine, 10% fetal bovine serum (FBS), 0.6% penicillin-streptomycin, hygromycin B (300 μg/ml), and geneticin (600 μg/ml). All cells were maintained at 37°C and 5% CO₂ in their respective media and were passage twice a week using nonenzymatic cell dissociation solution. The human cannabinoid 1 receptor (hCB₁-R) transfected cell line was used for cAMP-, pERK1/2-, and [35S]GTPγS-binding experiments.

### References

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- **Materials**

  WIN55212, CP55940, and Org 27569 [5-chloro-3-ethyl-1H-indole-2-carboxylic acid [2-(4-piperidin-1-yl-phenyl)-ethyl]-amide] were obtained from Toecis (Bristol, UK), and SR141716A (N-(piperidin-1-yl)-5-(4-chlorophenyl)-1-(2,4-dichlorophenyl)-4-methyl-1H-pyrazole-3-carboxamide hydrochloride) from the National Institute on Drug Abuse. PSNBAM-1 was synthesized by Prosidion Limited (Oxford, UK) as described by Bloxham et al., (2006) (patent). Bovine serum albumin (BSA), cell culture media, dithiothreitol (DTT), nonenzymatic cell dissociation solution, GDP, GTPγS, G418, l-glutamate, Krebs’ salts, penicillin/streptomycin, Tris buffer, and Triton X-100 were all obtained from Sigma-Aldrich (Poole, UK). [3H]CP55940 (128 Ci/mmol), [3H]CP55940 (44 Ci/mmol), and [3H]GTPγS (1250 Ci/mmol) were obtained from PerkinElmer Life Sciences Inc. (Boston, MA). [3H]-piperidinyl)-5-(4-chlorophenyl)-1-(2,4-dichlorophenyl)-4-methyl-1H-pyrazole-3-carboxamide ([3H]SR141716A; 43 Ci/mmol) was obtained from the National Institute on Drug Abuse.

- **Chinese Hamster Ovary hCB₁R Cells**

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Membrane Preparation

Mouse Brain Membrane Preparation. Whole brains from adult male MF1 mice were suspended in centrifugation buffer (320 mM sucrose, 2 mM EDTA, 5 mM MgCl₂) and the tissues were homogenized with an Ultra-Turrax homogenizer (Sigma-Aldrich, UK). Tissue homogenates were centrifuged at 1600g for 10 minutes and the resulting supernatant collected. This pellet was resuspended in centrifugation buffer, centrifuged as before, and the supernatant collected. Supernatants were combined before undergoing further centrifugation at 28,000g for 20 minutes. The supernatant was discarded and the pellet resuspended in buffer A (50 mM Tris, 2 mM EDTA, 5 mM MgCl₂ at pH 7.0) and incubated at 37°C for 10 minutes. Following the incubation, the suspension was centrifuged for 20 minutes at 23,000g. After resuspending the pellet in buffer A, the suspension was incubated for 40 minutes at room temperature before a final centrifugation for 15 minutes at 11,000g. The final pellet was resuspended in buffer B (50 mM Tris, 1 mM EDTA, 3 mM MgCl₂) and the final protein concentration, determined by Bio-Rad DC kit, was 1 mg/ml. All centrifugation procedures were carried out at 4°C. Prepared brain membranes were stored at −80°C and defrosted on the day of the experiment.

Cell Membrane Preparation. A large batch of hCB₁R cells was prepared by expanding the cell culture to twenty 220-ml flasks. To prepare cell membranes, cells were washed in phosphate-buffered saline and then incubated with phosphate-buffered saline containing 1 mM EDTA for 5 minutes. Cells were then harvested by scraping into the buffer and centrifuged at 400g for 5 minutes. Cells pellets were then resuspended in ice-cold buffer A (320 mM sucrose, 10 mM HEPES, 1 mM EDTA, pH 7.4) and homogenized using a glass dounce homogenizer. Cell homogenates were then centrifuged at 1600g for 10 minutes at 4°C and the supernatant was collected. The pellet was resuspended, homogenized, and centrifuged at 1600g, and the supernatant was collected. Supernatants were pooled before undergoing further centrifugation at 50,000g for 2 hours at 4°C. The supernatant was discarded and the pellet was resuspended in buffer B (50 mM HEPES, 0.5 mM EDTA, 10 mM MgCl₂, pH 7.4), aliquoted into 0.5-ml tubes, and stored at −80°C. Protein concentration was determined against a BSA standard curve using BioRad Bradford protein detection reagent.

Signaling Assays

[^35S]GTPγS Binding Assay

Mouse brain membranes (5 μg protein) or hCB₁R cell membranes (25 μg protein) were preincubated for 30 minutes at 30°C with adenosine deaminase (0.5 IU/ml). The membranes were then incubated with the agonist ∆ modulator or vehicle for 60 minutes at 30°C in assay buffer (50 mM Tris-HCl; 50 mM Tris-Base; 5 mM MgCl₂; 1 mM EDTA; 100 mM NaCl; 1 mM DTT; 0.1% BSA) in the presence of 0.1 nM[^35S]GTPγS and 30 μM GDP, in a final volume of 500 μL. Binding was initiated by the addition of[^35S]GTPγS. Nonspecific binding was measured in the presence of 30 μM GTPγS. The reaction was terminated by rapid vacuum filtration (50 mM Tris-HCl; 50 mM Tris-Base; 0.1% BSA) using a 24-well sampling manifold (cell harvester; Brandel, Gaithersburg, MD) and GF/B filters (Whatman, Maidstone, UK) that had been soaked in buffer (50 mM Tris-HCl; 50 mM Tris-Base; 0.1% BSA) for at least 24 hours. Each reaction tube was washed five times with a 1.2-ml aliquot of ice-cold wash buffer. The filters were oven-dried for at least 60 minutes and then placed in 4 ml of scintillation fluid (Ultima Gold XR, PerkinElmer, Cambridge, UK). Radioactivity was quantified by liquid scintillation spectrometry.

Data Analysis. Raw data were presented as cpm. Basal level was defined as zero. Results were calculated as a percentage change from basal level of[^35S]GTPγS binding (in the presence of vehicle). Data were analyzed by nonlinear regression analysis of sigmoidal dose-response curves using GraphPad Prism 5.0 (GraphPad, San Diego, CA). The results of this analysis are presented as E_max with 95% confidence interval (CI) and pEC₅₀ (logEC₅₀) ± S.E.M.

PathHunter CB₁ β-Arrestin Assays

PathHunter hCB₁ β-arrestin cells were plated 48 hours before use and incubated at 37°C, 5% CO₂ in a humidified incubator. Compounds were dissolved in dimethylsulfoxide (DMSO) and diluted in OCC media. Five μl of allosteric modulator or vehicle solution was added to each well and incubated for 60 minutes. Five μl of agonist was added to each well followed by a 90-minute incubation. Fifty-five μl of detection reagent was then added followed by a further 90-minute incubation at room temperature. Chemiluminescence, indicated as relative light units (RLU), was measured on a standard luminescence plate reader.

Data Analysis. Raw data were RLU. Basal level was defined as zero. Results were calculated as the percentage of CP55940 maximum effect. Data were analyzed by nonlinear regression analysis of sigmoidal dose response curves using GraphPad Prism 5.0 (GraphPad, San Diego, CA). The results of this analysis were presented as E_max with 95% CI and pEC₅₀ (logEC₅₀) ± S.E.M.

Cyclic AMP Assays

hCB₁R cells (0.6 × 10⁵ cells/ml) were preincubated in PBS containing 1 mg/ml BSA (assay buffer) for 30 minutes at 37°C with rolipram (10 μM). This was followed by further 30 minutes incubation at 37°C with cannabinoid agonist ∆ or Org 27569 or vehicle. A final incubation of 30 minutes with 5 μM forskolin in a total volume of 500 μl then took place. The reaction was terminated by addition 0.1 M HCl and centrifuged to remove cell debris. The pH was brought to 8 or 9 using 1 M NaOH and cyclic AMP content was then measured using a radioimmunoassay kit (The Biotrak; Amersham). Forskolin and rolipram were dissolved in DMSO.

Data Analysis. Results were calculated as the percentage inhibition of forskolin-stimulated cAMP production (pmol/mg). Data were analyzed by nonlinear regression analysis of sigmoidal dose response curves using GraphPad Prism 5.0 (GraphPad, San Diego, CA). The results of this analysis were presented as E_max with 96% CI and pEC₅₀ (logEC₅₀) ± S.E.M.

AlphaScreen SureFire ERK 1/2 Phosphorylation Assay

ERK1/2 MAP-Kinase Phosphorylation Assay. For experimental studies of ERK1/2 MAP-kinase phosphorylation, hCB₁R cells (40,000 cells/well) were plated onto 96-well plates and serum-starved for 24 hours. Cells were then washed with DMEM before the addition of agonist ∆ or Org 27569 or vehicle at the desired concentration. After a 6-minute incubation
at 37°C in a humidified atmosphere, ice-cold lysis buffer (provided with the AlphaScreen SureFire kit) was added to each well and the plate was placed at −80°C for at least 1 hour.

**AlphaScreen SureFire ERK Assay.** The assay was performed in 384-well white Proxiplates according to the manufacturer instructions. Briefly, 4-μl samples were incubated with 7 μl of mixture containing 1 part donor beads, 1 part acceptor beads, 10 parts activation buffer, and 60 parts reaction buffer. Plates were incubated for 3 hours at 25°C in the dark and read with the Envision system (PerkinElmer) using AlphaScreen settings.

**Data Analysis.** Raw data were presented as “Envision units.” Basal level was defined as zero. Results were presented as means and variability as S.E.M. or 95% CI of the percent stimulation of phosphorylated ERK1/2 above the basal level (in the presence of vehicle). Data were analyzed by nonlinear analysis of log agonist versus response curves using GraphPad Prism 5.0 (GraphPad, San Diego, CA). The results of this analysis were presented as *E* max with 95% CI and pEC 50 (logEC 50) ± S.E.M.

### Radioligand Binding Experiments

**Competition and Saturation Binding Assays**

**Mouse Brain Membranes.** Binding assays were performed with the CB1 receptor agonist [3H]CP55940 (0.7 nM for equilibrium or 0.1–10 nM for saturation) and CB1 receptor agonist [3H]WIN55212-2 (1.5 nM) in 1 mg/ml BSA and 50 mM Tris buffer, total assay volume 500 μl. Binding was initiated by the addition of mouse brain membranes (30 μg). Assays were carried out at 37°C for 60 minutes before termination by addition of ice-cold wash buffer (50 mM Tris buffer, 1 mg/ml BSA) and vacuum filtration using a 24-well sampling manifold (Brandel Cell Harvester, PerkinElmer) and Whatman GF/B glass-fiber filters that had been soaked in wash buffer at 4°C for 24 hours. Each reaction tube was washed five times with a 1.2-ml aliquot of buffer. The filters were oven-dried for 3 hours at 80°C for at least 2 hours before termination by the addition of mouse brain membranes (30 μg). Assays were carried out at 37°C for 60 minutes before termination by addition of ice-cold wash buffer (50 mM Tris buffer, 1 mg/ml BSA) and vacuum filtration using a 24-well sampling manifold (Brandel Cell Harvester, PerkinElmer) and Whatman GF/B glass-fiber filters that had been soaked in wash buffer at 4°C for 24 hours. Each reaction tube was washed five times with a 1.2-ml aliquot of buffer. The filters were oven-dried for 3 hours at 80°C for at least 2 hours before termination by the addition of mouse brain membranes (30 μg). Assays were carried out at 37°C for 60 minutes before termination by addition of ice-cold wash buffer (50 mM Tris buffer, 1 mg/ml BSA) and vacuum filtration using a 24-well sampling manifold (Brandel Cell Harvester, PerkinElmer) and Whatman GF/B glass-fiber filters that had been soaked in wash buffer at 4°C for 24 hours. Each reaction tube was washed five times with a 1.2-ml aliquot of buffer. The filters were oven-dried for 3 hours at 80°C for at least 2 hours before termination.

**hCB1R Cells.** Saturation and competition binding assays were performed by incubating 5–10 μg/well hCB1R cell membranes with a fixed concentration (K d or higher) of radioligand ([3H]CP55940) in assay buffer (50 mM Tris, 2.5 mM EDTA, 5 mM MgCl2, 1 mg/ml BSA, pH 7.4) at 30°C for various incubation times (1 minute to 2 hours) before termination of reactions by rapid filtration. For dissociation kinetic experiments, the radioligand was first incubated with membranes for 60 minutes to allow full association before an unlabeled competing ligand was added to each reaction at various time-points to initiate dissociation of the radioligand until reactions were terminated by filtration. Dissociation was initiated by the addition of 1 μM unlabeled ligand in the presence and absence of test compounds. For both association and dissociation assays, reactions were performed in duplicate or triplicate wells of 96-well, round bottom microtiter plates in a final volume of 200 μl. Following incubation, reactions were filtered onto GF/B filter mats presoaked in distilled H2O using a PerkinElmer Filtermate cell harvester. Filters were washed six times with ice-cold 50 mM Tris buffer, pH 7.4, then air dried and the

**Data analysis.** Saturation studies are generally carried out by measuring binding of a range of radioligand concentrations at equilibrium to a constant amount of receptor in the presence and absence of a high concentration of competing, unlabeled ligand. Specific binding data can then be analyzed using the following model based on the Hill-Langmuir equation:

\[
Y = \frac{B_{\text{max}} \times [A]}{[A] + K_d}
\]

Here, *Y* is specific binding, *B* max is the number of binding sites for the radioligand (*A*), K d is the equilibrium dissociation constant for *A*, and [A] is the concentration of this radioligand at half the maximum occupancy.

The saturation binding assay thus provides the affinity of the radioligand for the receptor, which is the concentration of radioligand that produces half of the maximum binding (K d), and the receptor density in the tissue under investigation, which is the level of maximum specific binding (B max). GraphPad Prism 5.0 (GraphPad, San Diego, CA) was used to calculate the K d ± S.E.M. and B max values with 96% CI.

**Association and Dissociation Binding Assays.** Association binding experiments were performed by incubating 5–10 μg/well hCB1R cell membranes with a fixed concentration (K d or higher) of radioligand ([3H]CP55940) in assay buffer (50 mM Tris, 2.5 mM EDTA, 5 mM MgCl2, 1 mg/ml BSA, pH 7.4) at 30°C for various incubation times (1 minute to 2 hours) before termination of reactions by rapid filtration. For dissociation kinetic experiments, the radioligand was first incubated with membranes for 60 minutes to allow full association before an unlabeled competing ligand was added to each reaction at various time-points to initiate dissociation of the radioligand until reactions were terminated by filtration. Dissociation was initiated by the addition of 1 μM unlabeled ligand in the presence and absence of test compounds. For both association and dissociation assays, reactions were performed in duplicate or triplicate wells of 96-well, round bottom microtiter plates in a final volume of 200 μl. Following incubation, reactions were filtered onto GF/B filter mats presoaked in distilled H2O using a PerkinElmer Filtermate cell harvester. Filters were washed six times with ice-cold 50 mM Tris buffer, pH 7.4, then air dried and the

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**Fig. 1.** Structures of Org 27569 (Org) and PSNCBAM-1 (PSN).
Radioactivity counted in a Microbeta Trilux liquid scintillation counter.

Data analysis. Kinetic binding assays can be used to calculate the association or dissociation rate constants of a radioligand. Association experimental data can be of use to establish the time of a radioligand to reach equilibrium and therefore provide an optimal incubation time for saturation or competition binding assays. Association experiments also provide an observed association rate, \( k_{\text{obs}} \), the association rate at a given concentration of radioligand, and maximum receptor occupancy at equilibrium (\( Y_{\text{max}} \)). Dissociation experiments provide a dissociation rate constant for the radioligand, \( k_{\text{off}} \), which can be used with \( k_{\text{obs}} \) to calculate the association rate constant \( k_{\text{on}} \) using Eq. 2.

\[
k_{\text{on}} = \frac{k_{\text{obs}} - k_{\text{off}}}{[A]} \tag{2}
\]

Data were analyzed using the one-phase association model in GraphPad Prism 5.0 (GraphPad, San Diego, CA) to calculate the \( k_{\text{obs}} \pm \text{S.E.M.}, Y_{\text{max}} \pm \text{S.E.M.}, \) and \( k_{\text{off}} \pm \text{S.E.M.} \).

Statistical Analysis. Values have been expressed as means and variability as S.E.M. or as 95% CI. Mean values have been compared using Student’s unpaired t test, one-sample tests, or analysis of variance (ANOVA) followed by Dunnett’s test or the Newman-Keuls test. P values < 0.05 were considered to be significant.

Results

Effect of Allosteric Modulators on CB₁ Receptor Agonist Signaling

\([\text{³²P}]\text{GTP}\gamma\text{S} \) Binding Assay in Brain Membranes. In mouse brain membranes, CP55940 stimulated \([\text{³²P}]\text{GTP}\gamma\text{S} \) binding with a pEC₅₀ value of 8.20 ± 0.11 and \( E_{\text{max}} \) of 62% (95% CI, confidence limits 56 and 69). The potency of
WIN55212 (pEC$_{50}$ = 7.84 ± 0.08) was not significantly different from that of CP55940, but the efficacy was significantly higher: $E_{\text{max}}$ of 98% (95% CI, confidence limits 90 and 107). Both allosteric modulators Org 27569 and PSNCBAM-1 (Fig. 1) produced a concentration-related reduction in the $E_{\text{max}}$ values for both CP55940 and WIN55212 (Fig. 2; Table 1). However, the compounds were significantly less effective as inhibitors of WIN55212 as compared with CP55940. Neither Org27569 nor PSNCBAM-1 significantly decreased the $E_{\text{max}}$ of WIN55212 until a concentration of 1 μM in comparison, the compounds inhibited the action of CP55940 in the nM range (Fig. 2; Table 1). Neither Org 27569 nor PSNCBAM-1 significantly altered the pEC$_{50}$ values of CP55940 or WIN55212 at any of the concentrations tested (Table 1). Org 27569 alone had no significant effect on [${}^{35}$S]GTP$_S$ binding in mouse brain membranes at concentrations of 1 nM to 10 μM (unpublished data).

Org 27569 also significantly decreased the efficacy of the endogenous cannabinoid anandamide (AEA) in this assay (Fig. 2E, Table 1). The endocannabinoid was more susceptible to inhibition by the allosteric modulator than WIN55212, with significant inhibition being observed in the presence of 100 nM Org 27569.

[${}^{35}$S]GTP$_S$ Binding Assay in hCB$_1$R Cell Membranes. In hCB$_1$-expressing cells, CP55940-stimulated [${}^{35}$S]GTP$_S$ binding with a pEC$_{50}$ value of 7.35 ± 0.19 and $E_{\text{max}}$ of 65% (95% CI, confidence limits 57 and 72). Neither the potency (pEC$_{50}$ = 6.70 ± 0.17) nor the efficacy ($E_{\text{max}}$ = 70.4%, 95% CI, confidence limits 61 and 79) of WIN55212 was significantly different from that of CP55940 (Fig. 3). Org 27569 alone had no significant effect on [${}^{35}$S]GTP$_S$ binding in mouse brain membranes at concentrations of 1 nM to 10 μM (unpublished data).

Neither Org27569 nor PSNCBAM-1 significantly decreased the $E_{\text{max}}$ values of CP55940 in the nM range (Fig. 2; Table 1). Neither Org27569 nor PSNCBAM-1 significantly altered the pEC$_{50}$ value of WIN55212 (pEC$_{50}$ = 8.70 ± 0.08) was not significantly different from that of CP55940, but the efficacy was significantly lower: $E_{\text{max}}$ of 98% (95% CI, confidence limits 77 and 98) and pEC$_{50}$ value of 8.01 ± 0.19. WIN55212 was significantly less potent with a pEC$_{50}$ value of 7.02 ± 0.20 (Student’s unpaired $t$ test) but had similar efficacy with an $E_{\text{max}}$ of 78.5% (95% CI, confidence limits 64 and 93). Org 27569 significantly reduced the $E_{\text{max}}$ for CP55940 at a concentration of 10 nM, with signaling being abolished in the presence of 100 nM Org 27569.

Cyclic AMP Assays in hCB$_1$R Cell Membranes. Next we measured the effect of Org 27569 on CB$_1$ agonist–mediated inhibition of forskolin-stimulated cAMP production in hCB$_1$R cells (Fig. 4, A and B). In the presence of vehicle, CP55940 inhibited forskolin-stimulated cAMP formation with an $E_{\text{max}}$ of 98.6% (95% CI, confidence limits 77 and 98) and pEC$_{50}$ value of 8.01 ± 0.19. WIN55212 was significantly less potent with a pEC$_{50}$ value of 7.02 ± 0.20 (Student’s unpaired $t$ test) but had similar efficacy with an $E_{\text{max}}$ of 78.5% (95% CI, confidence limits 64 and 93). Org 27569 significantly reduced the $E_{\text{max}}$ for WIN55212 at a concentration of 10 nM, with signaling being abolished in the presence of 100 nM of Org 27569 ($P < 0.001$, one-sample $t$ test) (Fig. 4B, Table 2). In the presence of vehicle, CP55940 and CP55540 the level of cAMP was significantly lower than basal (Fig. 4A). In contrast, Org 27569 was less effective as an inhibitor of WIN55212-mediated inhibition of forskolin-stimulated cAMP production (Fig. 4B, Table 2).

It has been previously demonstrated that CB$_1$ receptors couple to both G$_s$ and G$_i$ proteins and can stimulate or inhibit the formation of cAMP; thus in the presence of PTX, a simulation of cAMP is revealed (Glass and Felder, 1997; Glass and Piomelli, 1995). Hence, we measured the effect of Org 27569 on CB$_1$ agonist binding induced by CP55940 was abolished by 300 nM PSNCBAM-1. This concentration did not significantly affect the stimulation induced by WIN55212, the effect of which was only inhibited by micromolar concentrations of PSNCBAM-1.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Effect of Org 27569 and PSNCBAM-1 on CP55940- and WIN55212-stimulated [${}^{35}$S]GTP$_S$ binding in mouse brain membranes</th>
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<td>PSN (100 nM)</td>
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<td>PSN (1 μM)</td>
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</table>

$^a$ Negative logarithm of the agonist EC$_{50}$ value, determined using nonlinear regression analysis. Values represent the mean ± standard error of the mean (S.E.M.) of four to six experiments.

$^b$ Maximal agonist effect, determined using nonlinear regression analysis. Values represent the mean with 95% CI of four to six experiments.

$^c$ Significantly different (nonoverlapping confidence limits) from the DMSO vehicle control.
Bonhous et al., 1998). In line with this, we find that, after overnight treatment of hCB1R cells with PTX (5 ng/ml), CP55940 no longer inhibits but rather stimulates the production of cAMP; the $E_{\text{max}}$ for stimulation being 174% (95% CI, confidence limits 106 and 242) and the pEC$_{50}$ being (5.87 ± 0.35). On the other hand, Org 27569 alone in the absence of PTX pretreatment stimulates cAMP production, an effect that is maintained following PTX treatment (Fig. 4C). The $E_{\text{max}}$ for Org 27569 was 106% (95% CI, confidence limits 61 and 152) in the absence and 141% (95% CI, confidence limits 110 and 173) in the presence of PTX; the pEC$_{50}$ values for Org 27569 were 5.87 ± 0.28 in the absence and 6.44 ± 0.23 in the presence of PTX. Neither Org 27569 nor CP55940 had any effect on forskolin-stimulated cAMP production in untransfected CHO cells (Fig. 4C). Notably, the CB1 receptor orthosteric inverse agonist SR141 also produced an increase in cAMP levels ($E_{\text{max}}$ of 50%, 95% CI, confidence limits 32–68); an effect that was abolished after PTX pretreatment, indicating the effect was due to constitutive activation of G$_i$ (Fig. 4D).

The stimulation of cAMP produced by CP55940 in PTX pretreated cells was abolished by 100 nM Org 27569, a concentration which alone did not stimulate cAMP production (Fig. 4E).

In the absence of forskolin, CP55940 produced a very small stimulation of cAMP production reaching an $E_{\text{max}}$ of 11% (95% CI, confidence limits 7 and 14). Org 27569 did not significantly affect levels of cAMP in the absence of forskolin (Fig. 4F).

**ERK 1/2 Phosphorylation Assay in hCB1R Cell Membranes.** Using an AlphaScreen SureFire ERK 1/2 phosphorylation assay kit, we measured the effect of Org 27569 on activation of ERK 1/2 phosphorylation by CB1 agonists in hCB1R cells (Fig. 5, A and B). CP55940 induced rapid, transient ERK phosphorylation, which peaked at 6 minutes and rapidly decayed by 15–20 minutes (data not shown); this is similar to data obtained by others (Daigle et al., 2008). Subsequent analysis was conducted at the 6-minute time point. In the presence of vehicle, CP55940 induced ERK1/2 phosphorylation above basal with an $E_{\text{max}}$ of 50.0% (95% CI, confidence limits 44 and 56) and pEC$_{50}$ value of 7.69 ± 0.14. WIN55212 was significantly less potent with a pEC$_{50}$ value of 6.95 ± 0.42, but its efficacy did not differ from that of CP55940: $E_{\text{max}}$ value of 40.2 (95% CI, confidence limits 27 and 54).
In contrast to the inhibitory effects observed with Org 27569 in the other signaling assays, at 100 nM and 1 μM this compound significantly increased the \( E_{\text{max}} \) for CP55940-induced ERK 1/2 phosphorylation (Fig. 5A; Table 2). In the presence of 1 μM Org 27569, the basal level of the CP55940 log concentration-response curve was 15% (95% CI, confidence limits 6 and 24). Org 27569 had no significant effect on ERK 1/2 phosphorylation induced by WIN55212 (Fig. 5B, Table 2).

PathHunter \( \beta \)- Arrestin Assays. In the PathHunter \( \beta \)-arrestin CB1 assay (Fig. 6, Table 3), CP55940-stimulated \( \beta \)-arrestin recruitment with a \( pE_{50} \) value of 7.89 ± 0.06 and \( E_{\text{max}} \) of 99% (95% CI, confidence limits 70 and 104). The potency of WIN55212 (\( pE_{50} \) = 6.93 ± 0.14) was significantly lower than that of CP55940 (Student’s unpaired \( t \) test), but the efficacy was not significantly different; \( E_{\text{max}} \) of 83% (95% CI, confidence limits 70 and 97). The allosteric modulators, Org 27569 and PSNCBAM-1 produced a concentration-related increase in the \( E_{\text{max}} \) values of both CP55940 and WIN55212 (Fig. 6; Table 3). Neither Org 27569 nor PSNCBAM-1 significantly altered the \( pE_{50} \) values of CP55940 or WIN55212 at any of the concentrations tested (Table 3). Org 27569 also significantly decreased the efficacy of the endogenous cannabinoid anandamide (AEA) in this assay (Fig. 6E; Table 3). Org 27569 alone had no significant effect on \( \beta \)-arrestin recruitment (Fig. 6F).

As observed in the \( ^{[35]} \text{S} \)GTP\( \gamma \)S binding assay, the compounds were significantly less potent as inhibitors of WIN55212 as compared with CP55940. The IC\textsubscript{50} values for the inhibitors were calculated from concentration-response curves of the inhibitor concentration versus the percentage reduction in the agonist \( E_{\text{max}} \) value. The IC\textsubscript{50} values for Org 27569 against CP55940 and WIN55212 (Fig. 7) were 2.03 ± 0.37 nM and 10.17 ± 0.96 nM, respectively (\( P < 0.001 \), Student’s unpaired \( t \) test). Similarly, the IC\textsubscript{50} values for PSNCBAM-1 against CP55940 and WIN55212 (Fig. 7) were 2.72 ± 0.33 nM and 8.74 ± 0.78 nM, respectively (\( P < 0.001 \), Student’s unpaired \( t \) test).

**Single-Point Mutation (W5.43A) of the CB1 Receptor.** In view of the significant divergence of the effects of Org 27569 on CP55940 as compared with WIN55212, we investigated its effects in cells expressing the point mutation, W5.43A. McAllister et al. (2003) have demonstrated that WIN55212 is affected by W5.43A mutations, suggesting that these residues are part of the binding site for this ligand. In contrast, CP55940 is unaffected by this mutation. In wild type cells, 1 μM Org 27569 abolished CP55950 stimulation of \( ^{[35]} \text{S} \)GTP\( \gamma \)S binding. However, in the cells expressing the W5.43A point mutation of CB1, Org 27569 (1 μM) did not significantly alter the \( E_{\text{max}} \) for CP55940-induced stimulation of \( ^{[35]} \text{S} \)GTP\( \gamma \)S binding (Supplemental Fig. 1). These data suggest that there may be an overlap in the binding pocket for WIN55212 and Org 27569.

**Effect of Allosteric Modulators on CB1 Receptor Agonist Binding.**

**Equilibrium Binding Assays.** In line with our previous studies (Price et al., 2005), we find that Org 27569 causes a significant and concentration-dependent increase in the specific binding of \( ^{[3]} \)HCP55940 to mouse brain membranes with an \( E_{\text{max}} \) of 212 ± 11% and a \( pE_{50} \) of 6.38 ± 0.21 (Fig. 8A). Here we find that in mouse brain membranes PSNCBAM-1
similarly caused a $141 \pm 7.9\%$ increase in the specific binding of $[^{3}H]$CP55940 with a pEC$_{50}$ of 6.87 $\pm$ 0.46 (Fig. 8A). We have also previously reported (Price et al., 2005) that, in contrast to the increase in specific binding of $[^{3}H]$CP55940, Org 27569 caused a significant and concentration-related decrease in the specific binding of $[^{3}H]$SR141716A to mouse brain membranes; the displacement was incomplete and not consistent with a simple model of competitive displacement. We have also previously reported that, in hCB1R cells, PSNCBAM-1 caused a significant and concentration-dependent, increase in $[^{3}H]$CP55940 binding of $159 \pm 9\%$ with a pEC$_{50}$ of 8.08 $\pm$ 0.20 (Horswill et al., 2007). In hCB1R cells PSNCBAM-1 caused a significant and concentration-related decrease in the specific binding of $[^{3}H]$SR141716A with a pEC$_{50}$ of 5.65 $\pm$ 0.07; the displacement was incomplete and not consistent with a simple model of competitive displacement (Horswill et al., 2007).

Here we have investigated the effect of both compounds on the specific binding of $[^{3}H]$WIN55212 for the first time. In mouse brain membranes preparations, Org 27569 had no significant effect on the specific binding of $[^{3}H]$WIN55212 at concentrations of up to 10 $\mu$M (Fig. 8B). Unlabeled WIN55212 displaced $[^{3}H]$WIN55212 binding by $98 \pm 4\%$ with a pEC$_{50}$ of 8.21 $\pm$ 0.11 (Fig. 8B). PSNCBAM-1, at concentrations ranging from 1 nM to 10 $\mu$M, had a small but significant effect on the specific binding of $[^{3}H]$WIN55212 in mouse brain membranes (Fig. 8B). In the presence of PSNCBAM-1 $[^{3}H]$WIN55212 binding was increased to 109% (95% CI, confidence limits 107 and 111), which is significantly different from 100% (Fig. 8C). SR141716A fully inhibited $[^{3}H]$WIN55212 binding with a pK$_{i}$ of 8.02 $\pm$ 0.08 (Fig. 7C). This pK$_{i}$ value was...
consistent with that reported for SR141 against $[^{3}H]CP55940$ ($pK_a$ of 8.35 ± 0.11) (Horswill et al., 2007).

These data demonstrate that PSNCBAM-1 and Org 27569 display ligand dependence exhibited in the level of binding cooperativity exhibited with $[^{3}H]CP55940$ and $[^{3}H]WIN55212$.

**Saturation Binding Assays.** Saturation binding experiments involved investigating the equilibrium dissociation constant ($K_d$) and maximum occupancy ($B_{max}$) of the CB$_1$ receptor agonist radioligand $[^{3}H]CP55940$. $[^{3}H]CP55940$ bound in a saturable manner to mouse brain membranes (Fig. 9A; Table 4). Org 27569 (1 $\mu$M and 10 $\mu$M) significantly increased the $B_{max}$ of $[^{3}H]CP55940$ (Fig. 8A; Table 4).

However, the $pK_d$ of $[^{3}H]CP55940$ was unaffected by Org 27569 at either concentration. Similarly, PSNCBAM-1 significantly increased the $B_{max}$ value of $[^{3}H]CP55940$; neither 1 $\mu$M nor 10 $\mu$M PSNCBAM-1 significantly affected the $pK_d$ of $[^{3}H]CP55940$ in mouse brain membranes, however there was a trend toward an increase in $K_d$ (Fig. 8B; Table 4). Similarly, in saturation experiments using hCB$_1$R membranes (Fig. 8C; Table 4), the presence of 1 $\mu$M PSNCBAM-1 positively modulated binding of $[^{3}H]CP55940$ by increasing $B_{max}$ (Table 4). However, the $pK_d$ of $[^{3}H]CP55940$ was unaffected by PSNCBAM-1 ($P > 0.05$, Student’s $t$ test).

This increase in $B_{max}$ can be interpreted as an increase in the number of available binding sites for $[^{3}H]CP55940$. In parallel experiments, PSNCBAM-1 at 1 $\mu$M caused no change to the level of nonspecific binding of $[^{3}H]CP55940$ (data not shown). Thus the effect on $B_{max}$ would appear not to be a result of an increase in the level of nonspecific binding.

**Association and Dissociation Kinetics.** Competition and saturation experiments at equilibrium showed Org 27569 and PSNCBAM-1 to increase the binding of radiolabeled agonists. To gain greater understanding of the mechanisms underlying this effect, further detailed analysis of the effects of one of these modulators (PSNCBAM-1) on agonist association and dissociation was carried out with $[^{3}H]CP55940$ in hCB$_1$R cells.

$[^{3}H]CP55940$ (0.5 nM) bound to hCB$_1$R membranes with an observed association rate constant ($k_{ob}$) of 0.060 ± 0.008/minute and a maximum receptor occupancy at equilibrium ($Y_{max}$) of 1.59 ± 0.10 pmol/mg (Fig. 9C). When association of $[^{3}H]CP55940$ was measured in the presence of PSNCBAM-1 (2 $\mu$M), the compound had no effect on $k_{ob}$, values being 6.0 ± 0.8/min × $10^{-2}$ and 5.7 ± 0.4/min × $10^{-2}$ in DMSO- and PSN-treated, respectively ($P > 0.05$, Student’s $t$ test), but significantly elevated $Y_{max}$ of $[^{3}H]CP55940$; values being 1.59 ± 0.1 pmol/mg and 2.46 ± 0.21 pmol/mg in DMSO- and PSN-treated, respectively ($P < 0.05$, Student’s $t$ test); an increase of 55%, which corresponds closely to previously observed effects for this compound in competition binding assays.

$[^{3}H]CP55940$ dissociated from CB$_1$ receptors in a biphasic manner in the absence of PSNCBAM-1 (data were best fitted to a two-phase dissociation curve) (Fig. 9D). This was characterized by a fast phase during which 40.3 ± 1.9% of $[^{3}H]CP55940$ became dissociated, followed by a slow phase during which the remaining 59.7 ± 1.9% became dissociated. Approximately 20% of radioligand was not dissociated within the time of the experiment (120 minutes) but was predicted to become so from the trend of the curve. Such a biphasic relationship indicates that high- and low-affinity binding sites at the CB$_1$ receptor for $[^{3}H]CP55940$ are present in these membranes. A common explanation for this is that the fast phase corresponds to low-affinity binding and thus the radioligand dissociates from the receptor quickly, whereas the slow phase corresponds to high-affinity binding and thus the radioligand dissociates more gradually.

When PSNCBAM-1 was present during the dissociation phase at 0.1 $\mu$M and 2 $\mu$M, it caused a significant concentration-dependent increase in the proportion of slow phase dissociation (Fig. 9D; Table 5), such that its maximal effect produced 100% slow-phase dissociation (data were fitted best to a one-phase dissociation curve) ($P < 0.01$, one-way analysis of variance (ANOVA) followed by Dunnett’s...
multiple comparison). In the presence of 2 μM there was a slight alteration of the slow phase $k_{\text{off}}$ for $[^{3}H]CP55940$. When present, the fast phase $k_{\text{off}}$ was not significantly altered by 0.03 μM or 0.1 μM PSNCBAM-1 ($P > 0.05$, one-way ANOVA followed by Dunnett’s multiple comparison) but was decreased marginally by 2 μM PSNCBAM-1 ($P < 0.05$, one-way ANOVA followed by Dunnett’s multiple comparison). Thus, PSNCBAM-1 appeared to increase the proportion of high-affinity $[^{3}H]CP55940$ binding while not greatly affecting its dissociation rate.

**Effects of Gpp(NH)p.** Gpp(NH)p is a nonhydrolyzable analog of guanosine triphosphate and is known to cause uncoupling of G proteins from GPCRs. Such uncoupling of G proteins generally leads to a decrease in numbers of receptors in the high-affinity agonist binding conformation, thus reducing agonist binding. To establish whether the ability of PSNCBAM-1 to increase $[^{3}H]CP55940$ binding was dependent on G proteins being associated with CB1 receptors, binding experiments in the presence of PSNCBAM-1 were performed. Gpp(NH)p caused a concentration-dependent decrease in $[^{3}H]CP55940$ binding to hCB1R membranes. Gpp(NH)p at 100-μM concentration decreased the $pK_a$ of $[^{3}H]CP55940$ while apparently having little effect on $B_{\text{max}}$ (Fig. 10A); the $pK_a$ values were 0.89 nM (95% CI, confidence limits 0.54 and 1.23) and 3.11 nM (95% CI, confidence limits 1.30 and 4.90) in the presence and absence of Gpp(NH)p, respectively; the $B_{\text{max}}$ values were 3.84 pmol/mg (95% CI, confidence limits 3.32 and 4.35) and 4.09 nM (95% CI, confidence limits 2.82 and 5.36) in the presence and absence of Gpp(NH)p, respectively.

We also demonstrated that PSNCBAM-1 increases the $B_{\text{max}}$ of $[^{3}H]CP55940$ in both brain membranes and hCB1R cells (Fig. 9, A and B). The mechanism underlying this increase in $B_{\text{max}}$ remains to be established. However, one possible explanation for this increase is that it resulted from an increase in the number of receptors that are coupled to G protein—a condition that can give receptors higher affinity for agonist binding. If PSNCBAM-1 did indeed exert its effects through increased G protein association with receptors, then it might be expected to lose this property in the presence of Gpp(NH)p, in which receptors are uncoupled from G proteins. As displayed in Fig. 10B, 100 μM Gpp(NH)p significantly reduced 0.5 nM $[^{3}H]CP55940$ binding by 46 ± 0.4% as would
when Gpp(NH)p was present, PSNCBAM-1 not only blocked, binding experiments, PSNCBAM-1 significantly increased

be predicted from the data displayed in Fig. 10A (P < 0.01, one-way ANOVA followed by Bonferroni's multiple comparison). Similar to results obtain in previous equilibrium binding experiments, PSNCBAM-1 significantly increased [3H]CP55940 binding by 59 ± 8% (P < 0.01, one-way ANOVA followed by Bonferroni's multiple comparison). Surprisingly, when Gpp(NH)p was present, PSNCBAM-1 not only blocked the reduction in agonist binding caused by this agent, but also significantly increased the binding of [3H]CP55940 by 35 ± 0.1% above its level of binding in the absence of Gpp(NH)p (P < 0.01, one-way ANOVA followed by Bonferroni's multiple comparison). The difference between the effect of 1μM PSNCBAM-1 treatment in the presence and absence of Gpp(NH)p was not statistically significant indicating that Gpp(NH)p has little effect on agonist binding in the presence of PSNCBAM-1 (P > 0.05, one-way ANOVA followed by Bonferroni's multiple comparison). Hence PSNCBAM-1 apparently retained its ability to increase [3H]CP55940 binding even under conditions when CB1 receptors would be expected to be uncoupled from G proteins.

As shown in Fig. 10C, Gpp(NH)p (100 μM) affected [3H]CP55940 dissociation by decreasing the slow phase of dissociation from 57.4 (95% CI, confidence limits 54.6 and 59.8), to 29% (95% CI, confidence limits 25 and 33). This effect was the opposite of that produced by PSNCBAM-1 which increased the slow phase of dissociation (Fig. 9C). Like PSNCBAM-1, Gpp(NH)p caused only a small change in either the rapid or slow k_{off} values (Table 6). Hence Gpp(NH)p produced effects which are consistent with an increase in the proportion of high-affinity [3H]CP55940 binding sites. As also shown in Fig. 10C, in the presence of both PSNCBAM-1 (2 μM) and Gpp(NH)p (100 μM) the slow phase of [3H]CP55940 dissociation was 58% (95% CI, confidence limits 57 and 59) of total binding, a proportion which is very close to that in the absence of these agents. Again there was little change in the rapid or slow k_{off} values when both PSNCBAM-1 and Gpp(NH)p were present (Table 6). Thus, in dissociation experiments, PSNCBAM-1 appeared completely to reverse the effects of Gpp(NH)p (as was previously observed in equilibrium binding experiments).

**Discussion**

This study further highlights the unique pharmacological profile displayed by CB1 receptor allosteric modulators. Here we present a comprehensive characterization of the effects of
two allosteric modulators on a diverse range of CB1 receptor–coupled signaling pathways and on agonist-binding kinetics. Three major findings are presented here: These allosteric modulators display (1) ligand-dependent effects, (2) signaling pathway–dependent effects, and (3) effects on the maximum occupancy of CB1 receptor agonists.

Studies have highlighted differences in the ligand recognition site for WIN55212 (and other aminoalkylindoles) and that of structurally-distinct agonists, including CP55940 and anandamide (McAllister et al., 2003; Abood, 2005; Kapur et al., 2007). In particular, mutation of W5.43A results in a significant loss of affinity of WIN55212 and SR141716A, while the affinity of CP55940 was unaffected by this mutation (for review see Abood, 2005). In line with previous findings (Wang et al., 2011), here we show that the allosteric inhibitors display a marked ligand-selectivity in a broad range of CB1 receptor agonist signaling assays; both compounds are significantly less potent as inhibitors of WIN55212 signaling compared with CP55940, as measured in the [35S]GTPγS, β-arrestin, and cAMP assays. We find that neither compound affects the specific binding of [3H]WIN55212 at concentrations up to 10 μM. Furthermore, in cells expressing the CB1 mutation W5.43A, Org 27569 no longer inhibits CP55940-mediated signaling. Pharmacological and mutation studies also suggest a separation of the binding sites for the aminoalkylindoles from those of the other classes of cannabinoid ligands. For example the K3.28192 mutation has no effect on the affinity or efficacy of WIN55212 but causes a significant loss of affinity and efficacy of the other three classes of cannabinoid. In line with this, we find that the endocannabinoid anandamide and CP55940 are equally susceptible to antagonism by Org 27569, while the effect on WIN55212 is divergent. Taken together, the data suggest some commonality in the binding pocket for WIN55212 and that of the allosteric modulators, the consequence being that WIN55212 is less susceptible to antagonism by these compounds. It is important to note that it is possible that this mutation may not affect the affinity of Org 27569, but might rather affect the ability of the CB1R to transmit cooperativity between CP55940 and Org27569. Further radioligand binding studies and studies directed at identifying the location and function of the allosteric binding pocket are in progress.

We also found that Org 27569 displays an intriguing profile of signaling pathway specificity. The compound produces a marked inhibition of CP55940-induced stimulation of [35S]GTPγS binding in mouse brain membranes and hCB1R cells. Furthermore, it potently inhibits β-arrestin recruitment, which is PTX-insensitive. Org 27569 also apparently inhibits Gαi-mediated CP55940-induced inhibition of forskolin-stimulated cAMP production. As previously shown by others (Glass and Felder, 1997; Bonhaus et al., 1998; Chen et al., 2010), pretreatment of CB1R expressing cells with PTX unmask CB1 receptor-mediated, Gαi-coupled stimulation of cAMP production; Org 27569 (100nM) also abolished CP55940-induced increases in cAMP production. However, Org 27569 alone (at concentrations above 100nM) stimulated cAMP production; an effect that was unaffected by PTX pretreatment. Org 27569 had no effect on cAMP levels in the absence of forskolin. It is known that forskolin and Gαs synergize to activate adenyl cyclase (Barovsky and Brooker, 1985; Glass and Felder, 1997). Taken together, the data suggest that Org 27569 can act both as a CB1 receptor allosteric agonist of Gαs-coupled CB1 receptor signaling and (at lower concentrations) as an allosteric inhibitor of orthosteric agonist–induced activation of Gαs signaling. It is unlikely that the increase in cAMP observed with Org 27569 is inverse agonism of Gαi-mediated signaling because the effect is unaffected by PTX treatment. In contrast, the increase in cAMP observed with the CB1 receptor inverse agonist SR141716A is abolished by PTX pretreatment. Because the Org 27569 increases cAMP alone, it is not possible to conclude if the inhibition by this compound of CPP55940-induced inhibition of cAMP is due to inhibition Gαi–signaling or simply “physiologic antagonism” due to concomitant activation of Gαs.

In contrast to the inhibition of orthosteric agonist signaling observed in other assays, Org 27569 enhances CP55940-induced ERK phosphorylation. As observed for Gαs-mediated increases in cAMP, Org 27569 can also act as an allosteric
agonist (low-efficacy) to induce ERK phosphorylation; an effect which is Gαi-mediated because this effect is lost in the presence of PTX.

Ahn et al. (2012) have recently reported that Org 27569 acts as an inhibitor of both basal and agonist-induced G protein coupling in a [35S]GTPγS assay. However, Ahn et al. (2012) found that this compound alone, at the high concentration of 10 μM, promotes receptor internalization and increases ERK phosphorylation. Furthermore, the effects on pERK seemed to be G protein independent (PTX-insensitive). We also find that Org 27569 alone acts as a weak inverse agonist in the [35S]GTPγS assay but apparently as an agonist of Gαs signaling and a weak partial agonist of Gαi signaling in pERK assays, respectively. Furthermore we find that this compound alone has no effect on β-arrestin recruitment, which is known to be PTX-insensitive (van der Lee et al., 2009), but does act as an inhibitor of CB1 agonist–induced β-arrestin recruitment. In line with findings of Ahn et al. (2012), we also identify

### Table 4

Effect of allosteric modulators on saturation binding of [3H]CP55940 in mouse brain membranes and hCB1 cell membranes

<table>
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<tr>
<th>Modulator</th>
<th>Kd (95% CI)</th>
<th>Bmax (95% CI)</th>
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<td>Mouse Brain Membranes</td>
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<td></td>
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<tr>
<td>[3H]CP55 + Vehicle</td>
<td>2.67 (1.5–3.8)</td>
<td>1.59 (1.3–1.8)</td>
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<tr>
<td>[3H]CP55 + Org (1 μM)</td>
<td>2.16 (1.5–2.8)</td>
<td>2.43 (2.2–2.7)</td>
</tr>
<tr>
<td>[3H]CP55 + Org (10 μM)</td>
<td>2.76 (1.7–3.8)</td>
<td>3.25 (2.8–3.7)</td>
</tr>
<tr>
<td>[3H]CP55 + PSN (1 μM)</td>
<td>6.00 (3.1–8.9)</td>
<td>3.64 (2.7–4.5)</td>
</tr>
<tr>
<td>[3H]CP55 + PSN (10 μM)</td>
<td>5.66 (3.6–7.7)</td>
<td>2.98 (2.4–3.5)</td>
</tr>
<tr>
<td>hCB1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[3H]CP55 + Vehicle</td>
<td>0.45 (0.26–0.63)</td>
<td>6.4 (5.5–8.4)</td>
</tr>
<tr>
<td>[3H]CP55 + PSN (1 μM)</td>
<td>0.56 (0.45–0.66)</td>
<td>11 (10.8–12.2)</td>
</tr>
</tbody>
</table>

† Indicates the values are significantly different from vehicle as indicated by non-overlapping confidence limits.
marked divergence of the effect of Org 27569 on CB1 receptor agonist–induced ERK phosphorylation, whereby Org 27569 (100 nM and 1 μM) significantly increases the efficacy ($E_{\text{max}}$) of CP55940 as compared with inhibition observed in all other assays. Notably the ERK phosphorylation induced by CP55940 and Org 27569 is abolished after PTX treatment. Others have previously demonstrated that CB1-mediated ERK phosphorylation is Gαi-mediated (Chen et al., 2010); our results present a fascinating pharmacological profile for Org 27569, which apparently traffics CB1-mediated signaling, potentially inhibiting orthosteric agonist–mediated cellular events, mediated by cAMP and β-arrestin, while enhancing CB1-pERK–mediated cellular events.

There are well-documented examples of agonist-selective CB1 receptor coupling (reviewed by Bosier et al., 2010). For example, in the mouse tetrad, WIN55212 is more potent in reducing mobility than in producing antinociception, whereas CP 55940 is significantly more potent in reducing motor activity than producing catalepsy. Agonist-selective signaling or pharmacodynamic variations may underlie these ligand differences. Reports have identified the CB1-activated ERK signaling cascade as a key mediator of several forms of cocaine-induced synaptic plasticity, thereby implicating this cascade in addiction (Pan et al., 2011). It is conceivable that a CB1 receptor allosteric modulator may be designed that will selectively modulates pERK, thus providing a more targeted treatment of addiction. To our knowledge, the differential effects of Org 27569 described in this paper provide the first example of signal transduction–related biased antagonism of CB1 receptor signaling.

In an effort to understand the nature of the receptor modulation induced by Org 27569 and PSNCBAM-1, we carried out saturation binding studies. In these experiments both allosteric modulators surprisingly caused an elevation in $B_{\text{max}}$ of [3H]CP55940, indicating an increase in the number of available binding sites in the presence of these compounds. We observed no significant change in agonist affinity ($K_a$). This contrasts with the Org 27569-induced increase in [3H]CP55940 affinity with no change in maximum occupancy reported recently by Ahn et al. (2012), although notably, they did observe a trend toward an increase in $B_{\text{max}}$ in the presence of Org 27569.

In kinetic binding assays with [3H]CP55940 in CB1R cells, it appears that 60% of the CB1 receptors occupied by CP55940 are G protein-coupled (slow dissociation phase, high-affinity), whereas the remaining 40% are uncoupled (fast dissociation phase, low-affinity). The fact that the G protein uncoupling agent Gpp(NH)p reduced the slow phase of binding, and thus the fraction of receptors coupled to G proteins, supports this hypothesis. In hCB1R membranes, PSNCBAM-1 did not significantly affect either the observed association rate constant ($k_{\text{on}}$) or dissociation rate constant ($k_{\text{off}}$) of [3H]CP55940, but instead exerted a substantial effect on the proportions of fast and slow phases of dissociation. The $k_{\text{off}}$ of a ligand is highly reflective of its binding affinity and therefore any alteration of $k_{\text{off}}$ by a modulator may indicate a change in ligand affinity. The lack of substantial PSNCBAM-1 effects on CP55940 $k_{\text{off}}$ and $k_{\text{on}}$ implies that this compound causes very little alteration in CP55940 affinity. These results are consistent with saturation binding experiments at equilibrium.

### Table 5

<table>
<thead>
<tr>
<th>Slow Phase</th>
<th>$K_{\text{off (Slow)}}$</th>
<th>$K_{\text{off (Fast)}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[3H]CP55 + Vehicle</td>
<td>59.7 ± 1.9</td>
<td>1.1 ± 0.2</td>
</tr>
<tr>
<td>[3H]CP55 + 30 nM PSN</td>
<td>64.4 ± 3.9</td>
<td>1.2 ± 0.1</td>
</tr>
<tr>
<td>[3H]CP55 + 100 nM PSN</td>
<td>79.0 ± 4.0</td>
<td>0.9 ± 0.1</td>
</tr>
<tr>
<td>[3H]CP55 + 2 μM PSN</td>
<td>100 ± 0</td>
<td>0.4 ± 0.04</td>
</tr>
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</table>

Data shown are mean ± S.E.M. of 3 independent experiments. *P < 0.05, **P < 0.01 one-way ANOVA followed by Dunnett’s multiple comparison.

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**Fig. 10.** Effect of Gpp(NH)p and/or PSNCBAM-1 (1 μM) in hCB1R cell membranes on: (A) saturation binding of [3H]CP55940; (B) [3H]CP55940 equilibrium binding; (C) [3H]CP55940 dissociation. Data shown in (A) are mean values ± S.E.M. of triplicate wells from a single experiment that was performed twice. Data were best fitted using a one-site saturation binding model. Data shown in (B) are mean values ± S.E.M. of three independent experiments. **P < 0.01, #P > 0.05; one-way ANOVA followed by Bonferroni’s multiple comparison. Data shown in (C) are mean values ± S.E.M. of triplicate wells; the experiment was performed twice. Data for all groups were best fitted using a two-phase dissociation model.
where neither modulator altered the $K_d$ of [3H]CP55940. In contrast, the slow phase of CP55940 dissociation was greatly augmented from 60% in the absence of PSNCBAM-1 to 100% at the maximum PSNCBAM-1 concentration of 2 μM. Thus, consistent with the increase in $B_{max}$ observed in saturation binding assays, the presence of PSNCBAM-1 in kinetic assays appears to cause an increase in the proportion of high-affinity agonist binding sites.

Strikingly, PSNCBAM-1 retained its ability to augment CP55940 binding, even in the presence of Gpp(NH)p and blocked Gpp(NH)p effects on CP55940 dissociation. Hence, while Gpp(NH)p produced the expected effect of reducing agonist binding by uncoupling G proteins, PSNCBAM-1 effectively opposed this action in both equilibrium and kinetic binding experiments. This property of PSNCBAM-1 is consistent with its ability to increase the maximal number of binding sites ($B_{max}$). Thus, even under conditions when G proteins would not be expected to be associated with CB1 receptors, PSNCBAM-1 apparently induces a receptor conformation that displays a high affinity toward agonist compounds.

Previous investigations have demonstrated that structurally distinct ligands regulate CB1 receptor–G protein complexes with $G_{i1}$, $G_{i2}$, and $G_{i3}$ such that multiple conformations of the receptor can be evoked by ligands to regulate individual G proteins (Mukhopadhyay and Howlett, 2001, 2005; Anavi-Goffer et al., 2007). Mukhopadhyay and Howlett, (2005) found that the nonhydrolyzable GTP analog, GTPγS, promoted complete dissociation of all CB1 receptor–$G_{i}$ complexes; the CB1 agonist desacetyllevonantradol precluded GTPγS-induced dissociation of $G_{i3}$, while leaving $G_{i1}$ dissociation unaffected. In contrast, WIN55212 did not affect GTPγS-induced dissociation of any of the $G_{i}$ subtypes, which is consistent with the nonselectivity of this cannabinoid

| TABLE 6 | Effect of Gpp(NH)p and PSNCBAM-1 on [3H]CP55940 dissociation from hCB1 cell membranes |
| Control data are mean ± S.E.M. of three experiments. Data in the presence of Gpp(NH)p are mean with 95% CI of two independent experiments. |

<table>
<thead>
<tr>
<th>Slow Phase</th>
<th>K_{off} (Slow)</th>
<th>K_{off} (Fast)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>57.4 (54.6–59.8)</td>
<td>1.1 (0.7–1.7)</td>
</tr>
<tr>
<td>100 μM Gpp(NH)p</td>
<td>29 (25–33)†</td>
<td>2.2 (2.4–2.1)†</td>
</tr>
<tr>
<td>100 μM Gpp(NH)p + 2 μM PSN</td>
<td>58 (57–59)</td>
<td>0.9 (0.8–1.0)</td>
</tr>
</tbody>
</table>

† Significantly different (nonoverlapping confidence limits) from the DMSO vehicle.

Fig. 11. Summary of the complex pharmacology of the CB1 receptor allosteric modulators. Left, the effect of Org 27569 alone, and right, the effect of Org 27569 on binding and signaling of the CB1 receptor orthosteric ligand CP55940.
for Gα1 subtypes. It is conceivable that the biased antagonism observed here reflects the fact that allosteric modulators facilitate interactions with specific Gα subtypes while impeding interactions with others. The increase in \( B_{\text{max}} \) may be indicative of a high-affinity coupled complex that is coupled to a unique Gα pool that displays biased signaling. Differential effects of allosteric modulators on CP55940 and WIN55212 may also reflect differential Gα coupling of the agonist-allosteric bound receptor and warrant future investigation. Georgieva et al. (2008) found that CP55940 and WIN55212-bound CB1 receptor conformations have similar affinities for Gia1 but are profoundly different in their ability to activate this G protein type, WIN55212 being significantly more active. The finding presented here indicated that the modulators may promote the binding of a G protein subtype that binds to the CP-bound, but not the WIN-bound receptor.

Overall radioligand binding experiments indicate that the allosteric modulators Org 27569 and PSNCBAM-1 may be able to make available a population of CB1 receptors that retains the ability to bind agonists with high affinity but is not active in terms of its capacity to trigger certain CB1 agonist signaling responses. This hypothesis, that Org 27569 induces a high-affinity nonsignaling state, is also supported by data obtained by Ahn et al. (2012). Our data prompt an extension to this hypothesis, which is that in some functional assays the formation of the same complex will result in a loss of coupling to certain G proteins. Moreover, we find that Org 27569 alone can act as an agonist-allosteric bound receptor and warrant future investigations into its capacity to trigger certain CB1 agonist signaling.

References


