A Novel Aminotetralin-Type Serotonin (5-HT) \(_{2C}\) Receptor-Specific Agonist and 5-HT\(_{2A}\) Competitive Antagonist/5-HT\(_{2B}\) Inverse Agonist with Preclinical Efficacy for Psychoses

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ABSTRACT

Development of 5-HT\(_{2C}\) agonists for treatment of neuropsychiatric disorders, including psychoses, substance abuse, and obesity, has been fraught with difficulties, because the vast majority of reported 5-HT\(_{2C}\) selective agonists also activate 5-HT\(_{2A}\) and/or 5-HT\(_{2B}\) receptors, potentially causing hallucinations and/or cardiac valvulopathy. Herein is described a novel, potent, and efficacious human 5-HT\(_{2C}\) receptor agonist, (−)-trans-(2S,4R)-4-(3\(\text{[meta]}\))-bromophenyl)-N,N-dimethyl-1,2,3,4-tetrahydronaphthalen-2-amine (−)-MBP, that is a competitive antagonist and inverse agonist at human 5-HT\(_{2A}\) and 5-HT\(_{2B}\) receptors, respectively. (−)-MBP has efficacy comparable to the prototypical second-generation antipsychotic drug clozapine in three C57Bl/6 mouse models of drug-induced psychoses: the head-twitch response elicited by 2,5-dimethoxy-4-iodoamphetamine; hyperlocomotion induced by MK-801 [(5R,10S)-(−)-5-methyl-10,11-dihydro-5H-dibenzo[a,d]cyclohepten-5,10-imine hydrogen maleate (dizocilpine maleate)]; and hyperlocomotion induced by amphetamine. (−)-MBP, however, does not alter locomotion when administered alone, distinguishing it from clozapine, which suppresses locomotion. Finally, consumption of highly palatable food by mice was not increased by (−)-MBP at a dose that produced at least 50% maximal efficacy in the psychoses models. Compared with (−)-MBP, the enantiomer (−)-MBP was much less active across in vitro affinity and functional assays using mouse and human receptors and also translated in vivo with comparably lower potency and efficacy. Results indicate a 5-HT\(_{2C}\) receptor-specific agonist, such as (−)-MBP, may be pharmacotherapeutic for psychoses, without liability for obesity, hallucinations, heart disease, sedation, or motoric disorders.

Introduction

Psychotic disorders, which affect approximately 3% of the population (Perälä et al., 2007), are associated with an overactive striatal dopamine system (Abi-Dargham et al., 1998; Seeman and Seeman, 2014). Specifically, persons with schizophrenia are hypersensitive to psychostimulants (Curran et al., 2004), show elevated psychostimulant-induced dopamine release (Abi-Dargham et al., 1998), and display increased presynaptic dopamine synthesis in the striatum (Seeman and Seeman, 2014). Most existing antipsychotic medications interact primarily with dopamine D2 receptors to, theoretically, normalize dopamine signaling. Approximately two-thirds of patients, however, are noncompliant or cease taking their neuroleptic medication (Bellack, 2006), typically attributed to serious side effects that include weight gain, diabetes, high cholesterol, extrapyramidal symptoms, sedation, lethargy, and emotional dampening (NIMH, 2010; Moritz et al., 2013). Furthermore, extant antipsychotic drugs have limited efficacy in approximately one-third of patients (Lindenmayer, 2000), and so-called second-generation antipsychotic drugs do not have superior efficacy compared with their first-generation predecessors (Lieberman et al., 2005).

Targeting the serotonin (5-HT) system, and precisely the 5-HT\(_{2C}\) receptor, represents an alternative approach to pharmacotherapy for psychoses. 5-HT\(_{2C}\) receptors are expressed in several neural systems affected in schizophrenia, including the frontal cortex and the striatum (Lopez-Gimenez et al., 2000), and so-called second-generation antipsychotic drugs do not have superior efficacy compared with their first-generation predecessors (Lieberman et al., 2005).

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ABBREVIATIONS: AMP, amphetamine; CLOZ, clozapine; DOI, (±)-(2S,4R)-dimethoxy-4-iodoamphetamine; GPCR, G protein-coupled receptor; HEK293, human embryonic kidney 293 cells; 5-HT, serotonin; HTR, head-twitch response; (±)-MBP, (−)-trans-(2S,4R)-4-(3\([\text{meta}]\))-bromophenyl)-N,N-dimethyl-1,2,3,4-tetrahydronaphthalen-2-amine; MK-801, (5R,10S)-(−)-5-methyl-10,11-dihydro-5H-dibenzo[a,d]cyclohepten-5,10-imine hydrogen maleate (dizocilpine maleate); NMDA, N-methyl-D-aspartate; PAT, 4-phenyl-2-dimethylaminotetralin (4-phenyl-N,N-dimethyl-1,2,3,4-tetrahydronaphthalene-2-amine); Ro60-0175, (S)-(2S)-5-fluorindol-1-yloxy)-1-methylpropylamine.

310
the brain’s dopamine system. 5-HT_{2C} agonists and inverse agonists modulate dopamine release (Di Giovanni et al., 2000; De Deurwaerdere et al., 2004; Alex et al., 2005). 5-HT_{2C} receptor knockout mice possess enhanced baseline dopamine levels in the striatum and behavioral hypersensitivity to dopamine-releasing psychostimulants (Abdallah et al., 2009), and genetic manipulations that lead to overexpression of 5-HT_{2C} receptors alter dopamine metabolism (Kimura et al., 2009; Olaghere da Silva et al., 2010). In addition, induced-overexpression of dopamine D_{2} receptors increases expression of 5-HT_{2C} receptors (Simpson et al., 2011), and 5-HT_{2C} receptor ligands modulate D_{2} receptor activity (Olijslagers et al., 2004), further corroborating a physiologic link between 5-HT_{2C} receptors and central dopamine function. Finally, selective 5-HT_{2C} receptor agonists show preclinical efficacy in animal models of psychoses (Rosenzweig-Lipson et al., 2012). In clinical trials, the novel 5-HT_{2C} agonist vabicaserin showed proof-of-concept for treating schizophrenia (Shen et al., 2010), further corroborating a physiologic link between 5-HT_{2C} receptors and central dopamine function. Therefore, selective 5-HT_{2C} receptor agonists may be a novel approach to treating schizophrenia.

5-HT_{2C} receptors are also localized on pro-opiomelanocortin neurons in the hypothalamus, a brain region involved in regulating metabolism, hunger, and satiety signals. 5-HT_{2C} agonists stimulate the expression of anorexigenic pro-opiomelanocortin in the hypothalamus, resulting in decreased appetite (Lam et al., 2007; Xu et al., 2008). In clinical trials, lorcaserin, a 5-HT_{2} agonist with selectivity for the 5-HT_{2C} subtype (Thomsen et al., 2008), significantly reduced weight relative to placebo (Smith et al., 2010). Lorcaserin (Belviq) recently was approved by the U.S. Food and Drug Administration for treatment of obesity (Arena Pharmaceuticals, 2012). Thus, 5-HT_{2C} receptor agonists may reduce feeding and symptoms of psychoses by acting on independent neural systems. Furthermore, 5-HT_{2C} receptor agonists may show an improved safety profile in humans relative to existing antipsychotic drugs. This is observed in the clinic with aripiprazole (Abilify), which possesses 5-HT_{2C} receptor partial agonism and is associated with less weight gain compared with other antipsychotics drugs (Zhang et al., 2006; Leucht et al., 2013). Finally, because 5-HT_{2C} receptors are expressed predominantly in the central nervous system (Molineaux et al., 1989), compounds that specifically target and activate 5-HT_{2C} receptors should have limited impact on peripheral tissues, further decreasing the risk of side effects.

One common problem with most existing, selective 5-HT_{2C} agonists, including lorcaserin, is that they also activate 5-HT_{2A} and 5-HT_{2B} receptors at higher concentrations, which can lead to hallucinations (Glennon et al., 1984; Nichols, 2009) and cardiac valvulopathy, respectively (Rothman and Baumann, 2009). Pharmacological and behavioral data obtained using the novel and potent 5-HT_{2C}-specific agonist (−)-MBP are presented herein. (−)-MBP possesses high affinity at each of the 5-HT_{2C} receptors radiolabeled with an antagonist but high affinity at only 5-HT_{2C} receptors when 5-HT_{2} receptors are radiolabeled with an agonist. With regard to 5-HT_{2C}-G_{q}-mediated phosphoinositide hydrolysis signaling, (−)-MBP activates only the 5-HT_{2C} receptor subtype from both mouse and human cDNA. In addition, (−)-MBP behaves as a competitive antagonist of 5-HT at 5-HT_{2A} and 5-HT_{2B} receptors and also as an inverse agonist at 5-HT_{2B} receptors. In vivo, (−)-MBP displays anorexigenic and antipsychotic activity in mouse models but does not alter locomotion. The data suggest a 5-HT_{2C} receptor-specific agonist such as (−)-MBP may be pharmacotherapeutic for psychoses, without liability for obesity, hallucinations, heart disease, sedation, or motoric disorders.

### Materials and Methods

#### Compounds

The (−)-(2R, 4S)- and (−)-(2S, 4R)-trans enantiomers of 4-phenyl-3'-bromo-N,N-dimethyl-1,2,3,4-tetrahydronaphthalene-2-amine ([−]-MBP) and (−)-MBP, respectively, were purchased from PerkinElmer Life and Analytical Sciences (Waltham, MA). ([−]-MK-801 [(5R,10S)-(−)-5-methyl-10,11-dihydro-5H-dibenzo[a,d]cyclohepten-5,10-imine hydrogen maleate (dizocilpine maleate)], d-amphetamine sulfate, clozapine hydrochloride, mianserin hydrochloride, and (±)-2,5-dimethoxy-4-iodoamphetamine hydrochloride (DOI) were purchased from Sigma-Aldrich (St. Louis, MO). Compounds were weighed with accuracy ± 0.001 mg on a microanalytical balance (model XP26; Mettler-Toledo, Columbus, OH). Solutions of all compounds used for behavioral assays were made fresh on the day of testing. [3H]Mesulergine, [3H]ketanserin, [3H]5-HT, and [3H]mioinostol at commercially available specific activity were purchased from PerkinElmer Life and Analytical Sciences (Waltham, MA).

#### In Vitro Pharmacology

**Radioligand Binding and Phosphoinositide Hydrolysis Assays.** Antagonist radioligand receptor binding assays were performed in 96-well plates based on procedures previously described elsewhere (Canal et al., 2013). In brief, human embryonic kidney 293 (HEK293) cells were transfected with 10 μg of human 5-HT_{2A}, 5-HT_{2B}, or 5-HT_{2C}-ini receptor cDNA or 10 μg of mouse 5-HT_{2A} or 5-HT_{2C}-vnv receptor cDNA using Lipofectamine 2000 reagent (Invitrogen/Life Technologies, Carlsbad, CA) per the manufacturer’s instructions (mouse 5-HT_{2B} cDNA was not procured). Cell membranes were collected 48 hour later. (+)- or (−)-MBP, at increasing concentrations from 0.1 nM to 10 μM, was used to compete for receptor orthosteric binding sites labeled with 1 nM [3H]ketanserin (5-HT_{2A}) or 2 nM [3H]mesulergine (5-HT_{2B}, 5-HT_{2C}), and 10 μM mianserin was used to define the nonspecific antagonist radioligand binding at all three 5-HT_{2} subtypes. Both enantiomers were tested for affinities at antagonist-labeled 5-HT_{2} subtypes. Only (−)-MBP was competitive at 5-HT_{2C} receptors, consistent with its binding profile at 5-HT_{2A} and 5-HT_{2B} receptors.
tested in agonist competition binding assays wherein \[^{3}H\]5-HT at 3.7 nM (calculated) was used to label the 5-HT₄ subtypes. 5-HT at 10 \(\mu M\) was used to define nonspecific agonist radioligand binding. The assay buffer for competition with \[^{3}H\]5-HT contained 50 mM Tris·HCl, 3 mM CaCl₂, 10 \(\mu M\) pargyline, and 0.1% ascorbic acid. After a 120-minute equilibration period at room temperature, the incubation mixtures were rapidly passed through GF/B filters using a Mach 2 cell harvester (Tomtec, Hamden, CT) and subsequently washed with 50 mM Tris·HCl. Filter disks were placed in vials containing 2 ml of scintillation cocktail (SciIntVero; Thermo Fisher Scientific, Waltham, MA) and counted for \(^{3}H\)-induced scintillation using a Beckman-Coulter LS6500 counter (Indianapolis, IN).

5-HT₁ receptor-mediated inositol phosphate hydrolysis assays to measure functional responses of (+)- and (-)-MBP and 5-HT (positive control agonist) were performed as previously described elsewhere (Canal et al., 2013). In brief, transiently transfected HEK293 cells were labeled with 1 \(\mu Ci/ml\) \[^{3}H\]myoinositol and seeded into 48-well plates. Cells were treated with test compounds for 30 minutes. The reaction was stopped by addition of 50 mM formic acid. Anion-exchange columns (Bio-Rad Laboratories, Hercules, CA) were used to bind and collect \[^{3}H\]inositol phosphates. \(^{3}H\)-Induced scintillations then were measured. Competitive antagonism studies were performed with (-)-MBP only. In these studies, 0.1–10 \(\mu M\) (-)-MBP was used to compete with 0.0001–10 \(\mu M\) 5-HT for activation of 5-HT₂A and 5-HT₂B receptors. HEK293 cells transiently expressing each one of the 5-HT₂ subtypes were treated with (-)-MBP and 5-HT simultaneously for 30 minutes before stopping the reaction, as noted previously. Each binding and function experiment included triplicate measurements for each concentration of test compound, and each experiment was performed a minimum of three times.

**Statistics.** Binding data were analyzed using nonlinear regression, curve-fitting algorithms in GraphPad Prism version 6.00 for Microsoft Windows (San Diego, CA). Hill slopes were constrained to 1.0, consistent with the limited number of data points (Motulsky and Christopoulos, 2003). Ligand affinity is expressed as an approximation of \(K_i\) values by conversion of the IC₅₀ data using the equation \(K_i = IC_{50}/L/KD\), where \(L\) is the concentration of radioligand (Cheng and Prusoff, 1973). Data from phosphoinositide hydrolysis assays are presented as half-maximum (EC₅₀), half-minimum (IC₅₀), and maximum (E_MAX) values, representing potency and efficacy, as computed using GraphPad nonlinear regression curve-fitting algorithms. Agonist efficacy is presented as a percentage of the maximum 5-HT response. Inverse agonist efficacy is presented as a percentage of the basal values (scintillation counts per minute).

**In Vivo Behavioral Pharmacology**

**Subjects.** Male C57Bl/6 mice were obtained at ~8 weeks of age from The Jackson Laboratory (Bar Harbor, ME) for head-twitch response (HTR) and locomotion studies or Harlan Laboratories (Indianapolis, IN) for the food studies; they were allowed to acclimate to the temperature (23°C) and humidity-controlled vivarium for at least 1 week before testing. The vivarium was illuminated from 7:00 AM to 7:00 PM. Mice were housed in pairs for HTR and locomotion studies and singly for food studies. Standard rodent pellets (Purina 5001; LabDiet, St. Louis, MO) were available ad libitum, along with drinking water. Experiments were conducted at approximately the middle of the light phase.

(+)- or (-)-MBP, clozapine, or DOI was dissolved in sterile 0.9% saline or Milli-Q water (Millipore Corp., Billerica, MA). Clozapine was used as the comparative antipsychotic drug and positive control in all psychoses behavioral models. All compounds were administered systemically (by intraperitoneal or subcutaneous injection) in a volume of 0.01–0.02 ml/g body weight. All behavioral procedures were approved by the University of Florida and Northeastern University Institutional Animal Care and Use Committee and were performed in accordance with the Guide for the Care and Use of Laboratory Animals.

**DOI-Elicited Head-Twitch Response and Locomotion.** Experimentally naive mice were habituated to the testing room for approximately 30 minutes. Testing consisted of administration (subcutaneously) of Milli-Q water (vehicle), (+)- or (-)-MBP (3.0, 5.6, or 10.0 mg/kg), or clozapine (0.1 or 1.0 mg/kg) followed 10 minutes later by an injection of the 5-HT₂ antagonist DOI (1.0 mg/kg). Ten minutes later, mice were placed into a clear Plexiglas open-field chamber (43 × 43 cm; Med Associates, St. Albans, VT) for a 10-minute observation period. During this session, HTRs, defined as a clear, rapid, and discrete back-and-forth rotation of the head, were counted by a trained observer (D.M.) who had been blinded to the drug treatment conditions. A camera videotaped the session, and activity (distance traveled in cm) was calculated by Ethovision software (Noldus Information Technology, Leesburg, VA).

**MK-801-Elicited Hyperlocomotion.** Experimentally naive mice were habituated to the testing room for approximately 30 minutes. Locomotor activity testing consisted of administration (intraperitoneally) of saline (vehicle), clozapine (0.1 or 1.0 mg/kg), or (-)-MBP (3.0, 5.6, and 10.0 mg/kg), followed 10 minutes later by an injection of vehicle or the N-methyl-D-aspartate (NMDA) antagonist MK-801 (0.3 mg/kg). Mice were immediately placed into one of four opaque Plexiglas chambers (29.2 × 17.8 cm, 43.2 cm tall; Magnum Wood LLC, Gainesville, FL) for a 60-minute session. An overhead camera videotaped the session, and activity (distance traveled in cm) was calculated by Ethovision software (Noldus Information Technology, Leesburg, VA) to examine the time course of behavioral activity, (-)-MBP (10.0 mg/kg) was administered 10 minutes, 1 hour, or 3 hours before MK-801 (0.3 mg/kg) administration, and locomotion was assessed for 60 minutes thereafter.

**Amphetamine-Elicited Hyperlocomotion.** Experimentally naive mice were habituated to the testing room for approximately 30 minutes. Locomotor activity testing consisted of administration (i.p.) of saline (vehicle), clozapine (0.1 and 1 mg/kg), or (-)-MBP (3.0, 5.6, and 10.0 mg/kg), followed 10 minutes later by an injection of vehicle or the dopamine and norepinephrine transporter inhibitor and the substrate amphetamine (3.0 mg/kg). Locomotion was assessed exactly as noted in the MK-801 experiment. The effects of clozapine (1 mg/kg) or (-)-MBP (10 mg/kg) alone on locomotion were also tested during these experiments; the timing of injections and behavioral testing remained consistent.

**Palatable Meal Eating.** Mice were adapted to eating a supplemental treat of Fruit Crunchies (Bio-Serv, Frenchtown, NJ), which are 190-mg pellets of purified materials that contain a similar macronutrient balance and caloric density (3.45 kcal/g) as chow. Mice were presented 10 Crunchies, including at least three in each of the three flavors, in 10 ml glass jars suspended inside the cage via a metal stirrup. On the first day, access was for 24 hours, but thereafter daily access was rapidly tapered to 30 minutes, starting at ~14:00 hours. Crunchies were presented 5 days per week (Monday–Friday). After 30 minutes, uneaten Crunchies or halves were retrieved and the intake recorded. Each week, intakes on Tuesday through Thursday were used to compute a mean baseline for each mouse, and three groups were formed that were matched with this baseline. Friday was the test day on which animals were injected (intraperitonically) with (-)-MBP, (+)-MBP (6 or 12 mg/kg), or saline. Crunchies were presented 15 minutes later, and intake was measured as before, expressed as a percentage of each individual’s baseline for that week. Mice were tested repeatedly with different drugs and doses at 1-week intervals. Testing occurred during 2 weeks that were not consecutive.

**Statistics.** The dependent measures were analyzed by one- or two-way analysis of variance (ANOVA) with multiple comparisons (Newman-Keuls, Tukey’s, Dunnett’s test) or by unpaired two-tailed t tests, as appropriate, using commercially available statistical software (Sigmapastat 3.1; Systat Software, San Jose, CA and GraphPad Prism 6.00; GraphPad Software, San Diego, CA). \(P < 0.05\) was considered statistically significant. ED₅₀ values and 95% confidence intervals (CI) were determined using log-linear interpolation from the descending limb of the dose-effect curves.
Results

In Vitro Pharmacology

Affinity (Kᵰ) and function (EC₅₀, E_MAX, relative to 5-HT, and IC₅₀, I_MAX, relative to basal baseline) for (+)-MBP and (-)-MBP at each of the 5-HT₂ receptors are shown in Table 1. At human 5-HT₂ₐ, 5-HT₂ₕ, and 5-HT₂ₖ receptors labeled with antagonist radioligand, (-)-MBP had 17-, 2-, and 18-fold higher affinity (Kᵰ), respectively, in comparison with (+)-MBP. Likewise, at mouse 5-HT₂ₐ and 5-HT₂ₖ receptors labeled with antagonist radioligand, (-)-MBP had much higher affinity (20- and 88-fold, respectively) than (+)-MBP. At human 5-HT₂ receptors labeled with agonist radioligand, (-)-MBP had much higher affinity for the 5-HT₂ₖ subtype, with greater than 8- and 20-fold binding selectivity for 5-HT₂ₖ over 5-HT₂ₐ and 5-HT₂ₕ receptors, respectively.

Results from functional assays (data summarized in Table 1) revealed that (-)-MBP exclusively activated human and mouse 5-HT₂ₖ receptors (Fig. 2). (-)-MBP agonist potency at human 5-HT₂ₖ receptors (EC₅₀ = 19 nM) was 6-fold higher than its potency at mouse 5-HT₂ₖ receptors (EC₅₀ = 115 nM), and in both cases, maximum efficacy was approximately 60% compared with 5-HT (Fig. 2). (+)-MBP did not activate human or mouse 5-HT₂ₐ receptors at concentrations up to 10 μM (Fig. 2) and was a competitive antagonist of 5-HT activation of 5-HT₂ₐ receptors (Fig. 3A), with a mean (±S.E.M.) Kᵰ value of 441 (45) nM and pA₂ value of 2.64 (0.05). At human 5-HT₂₉ receptors, (-)-MBP was an inverse agonist (Fig. 3B), with a mean (±S.E.M.) IC₅₀ value of 112 (24) nM, and (-)-MBP also was a competitive antagonist of 5-HT activation of 5-HT₂₉ receptors (data not shown), with a mean (S.E.M.) Kᵰ value of 313 (118) nM and pA₂ value of 2.43 (0.17). In contrast to the discriminating 5-HT₂ functional pharmacology of (-)-MBP, (+)-MBP was a low potency, partial agonist at each of the human and mouse 5-HT₂₉ receptor subtypes (Table 1). Accordingly, further molecular pharmacologic characterization of (+)-MBP was not pursued, and (-)-MBP was designated the lead stereoisomer in light of its higher affinity and specific agonist activity at 5-HT₂ₖ receptors.

In Vivo Pharmacology

(-)-MBP Reduces the DOI-Elicited Head-Twitch Response without Altering Locomotion. Administration of DOI (1.0 mg/kg) (preceded by a vehicle injection) resulted in 37.1 (± 1.4) HTRs during the 10-minute session (Fig. 4). All doses of both enantiomers of MBP attenuated this response (F₆,₃₀ = 28.1; P < 0.0001). This effect was dose dependent (F₂,₂₄ = 11.69; P < 0.0001), with the (+) and (-) enantiomers reducing the number of DOI-elicited HTRs by 86% and 55%, respectively, at doses of 10.0 mg/kg (Fig. 4). (-)-MBP was more potent (F₁,₂₄ = 26.1; P < 0.0001) and had an ED₅₀ (± 95% CI) value of 2.67 (1.69-4.20) mg/kg compared with 8.80 (5.26-14.73) mg/kg for (+)-MBP. Clozapine also dose-dependently blocked the DOI-elicited HTR (P < 0.05) (Fig. 4). A linear regression analysis of data from Fig. 4A showed that the slopes of the lines from each group were statistically different (F₂,₅₂ = 28.7; P < 0.0001); rank order of potency was clozapine > (-)-MBP > (+)-MBP. During HTR sessions, locomotor activity was recorded. There was no combination of DOI and (-)-MBP doses that resulted in activity levels different from vehicle or DOI administration. In contrast, (+)-MBP at 10 mg/kg, in combination with DOI (1.0 mg/kg) resulted in decreased activity relative to vehicle plus DOI (P < 0.05), but not vehicle alone. Conversely, clozapine at 1 mg/kg alone (see below) or in combination with DOI (1.0 mg/kg) significantly decreased locomotion relative to vehicle (mean difference 1254 cm; 95% CI 50–2458; P < 0.05) and DOI alone (mean difference 1742 cm; 95% CI 857–2627; P < 0.05) (Fig. 4, inset).

(-)-MBP Reduces MK-801-Elicited Hyperlocomotion, an Effect Lasting at Least 2 Hours. MK-801 (0.3 mg/kg) administration resulted in increased levels of activity relative to vehicle administration (Fig. 5) that persisted for at least 60 minutes (Figs. 5, inset, and 6). (-)-MBP dose-dependently decreased MK-801 hyperlocomotion, which was significant at 5.6 mg/kg (mean difference 8654 cm; 95% CI 352–16,955; P < 0.05) and 10 mg/kg (mean difference 14,872 cm; 95% CI 6571–23,174; P < 0.005). The attenuation of MK-801-elicited activity was apparent throughout the entire 60-minute session (F₂₃₆,₂₃₄₈ = 4.43; P < 0.0001). The results with (-)-MBP were similar to clozapine, which also dose-dependently reduced MK-801-elicited hyperlocomotion (Fig. 5).

To examine the time course of behavioral activity, (-)-MBP (10.0 mg/kg) was administered 10 minutes, 1 hour, or 3 hours before MK-801 administration, and locomotor activity was assessed for 60 minutes thereafter (Fig. 6). At a 10-minute pretreatment time, there was a complete attenuation of MK-801's effects in which activity levels decreased from ~25,000 cm to ~10,000 cm (Fig. 6; mean difference 15,533 cm; 95% CI

<table>
<thead>
<tr>
<th>Compound</th>
<th>In Vitro Pharmacology</th>
<th>h₅-HT₂ₐ</th>
<th>h₅-HT₂ₕ</th>
<th>h₅-HT₂₉</th>
<th>m₅-HT₂₉</th>
<th>m₅-HT₂₉</th>
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<tr>
<td>(-)-MBP</td>
<td>Kᵰ antagonist labeled</td>
<td>20 (4.5)</td>
<td>13 (5.2)</td>
<td>12 (2.8)</td>
<td>26 (2.3)</td>
<td>11 (2.5)</td>
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<tr>
<td></td>
<td>Kᵰ agonist labeled</td>
<td>77 (14)</td>
<td>199 (35)</td>
<td>9.1 (6.5)</td>
<td>Not tested</td>
<td>Not tested</td>
</tr>
<tr>
<td></td>
<td>Function</td>
<td>pA₂ = 2.64 (0.05)</td>
<td>IC₅₀ = 112 (24)</td>
<td>EC₅₀ = 19 (3)</td>
<td>No activation @ 10 μM</td>
<td>EC₅₀ = 115 (4)</td>
</tr>
<tr>
<td>Efficacy</td>
<td>No activation @ 10 μM</td>
<td>69 (5) (inverse agonist)</td>
<td>63 (13) (agonist)</td>
<td>534 (63.0)</td>
<td>EC₅₀ &gt; 1000</td>
<td>969 (77.5)</td>
</tr>
<tr>
<td>(+)-MBP</td>
<td>Kᵰ antagonist labeled</td>
<td>332 (42.1)</td>
<td>31 (7.1)</td>
<td>200 (24.1)</td>
<td>EC₅₀ &gt; 1000</td>
<td>81 (8) (agonist)</td>
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<td></td>
<td>Function</td>
<td>EC₅₀ &gt; 1000</td>
<td>EC₅₀ &gt; 1000</td>
<td>EC₅₀ &gt; 1000</td>
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<td>30 (5) (agonist)</td>
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<td>Efficacy</td>
<td>34 (4) (agonist)</td>
<td>42 (6) (agonist)</td>
<td>81 (8) (agonist)</td>
<td>30 (5) (agonist)</td>
<td>57 (10) (agonist)</td>
<td></td>
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</tbody>
</table>

*₅HT₂₉-c, human 5-HT₂₉-α₁ isoform; m₅-HT₂₉ = mouse 5-HT₂₉-α₁ isoform.
*For efficacy, the percentage of basal signaling (inverse agonism).
*For efficacy, the percentage of maximal 5-HT response (agonism).
5-HT₂A, 5-HT₂B, and 5-HT₂C receptors compared with 5-HT.

![Graph](image)

**Fig. 2.** Representative functional responses of (-)-MBP at human 5-HT₂A, 5-HT₂B, and 5-HT₂C receptors compared with 5-HT.

7805–23,261; P < 0.005). When (-)-MBP was administered at a 1-hour pretreatment time (thus assessing behavioral activity from hours 1 to 2), attenuation of the MK-801 behavioral effects was still apparent throughout most of the session (mean difference 9540 cm; 95% CI 1813 to 17,268; P < 0.05). When administered 3 hours before the session, (-)-MBP had little effect on MK-801 elicited hyperactivity. (+)-MBP was not tested in this assay because of its relatively poor activity in the DOI-elicited-HTR model, which putatively reflects its low affinity and partial agonist functional activity at 5-HT₂A and 5-HT₂C receptors (Table 1).

(-)-MBP Reduces Amphetamine-Elicited Hyperlocomotion but Does Not Alter Locomotion When Administered Alone. Amphetamine (3.0 mg/kg) administration resulted in significantly increased levels of activity relative to saline administration, which lasted for at least 60 minutes (Fig. 7; P < 0.001). (-)-MBP at 10 mg/kg significantly decreased amphetamine-induced hyperactivity (mean difference 11,506 cm; 95% CI 4071–18,942; P < 0.001). The attenuation of amphetamine-elicited activity was apparent throughout the entire 60-minute session (F(238,2832) = 3.46; P < 0.0001). Also, clozapine at 1 mg/kg (mean difference 17,187 cm; 95% CI 8874–25,500; P < 0.001) but not 0.1 mg/kg significantly decreased amphetamine-elicited hyperactivity (Fig. 7). Clozapine also significantly reduced locomotor activity when administered alone (P < 0.005), but even the highest dose of (-)-MBP (10 mg/kg) did not significantly alter locomotor activity when administered alone (P = 0.14). (+)-MBP was not tested in this assay because of its relatively poor activity in the DOI-elicited-HTR model.

(-)-MBP Reduces Palatable Food Eating. Both (-)-MBP and (+)-MBP produced a dose-related suppression of intake of Crunchies (Fig. 8). (-)-MBP was significantly more potent and efficacious than (+)-MBP, similar to the effects seen in the DOI-elicited HTR tests. The main effect of dose was statistically significant (P < 0.001), the difference between (-)- and (+)-MBP was marginally significant (P = 0.054), and the dose x drug interaction was not significant. At 6 and 12 mg/kg, (-)-MBP reduced feeding to a mean (± S.E.M.) of 59.7% (6.3) and 35.8% (7.5), respectively, below the vehicle-treated group (both doses, P < 0.05). At 6 and 12 mg/kg, (+)-MBP reduced feeding to a mean (± S.E.M.) of 82.9% (8.0) and 55.1% (6.4), respectively, below the vehicle-treated group (6 mg/kg, not significant; 12 mg/kg, P < 0.05). From linear regressions (r² = 0.59, 0.69, P < 0.01), the estimated ED₅₀ values for (-)-MBP and (+)-MBP were 9.6 and 13.6 mg/kg, respectively.

**Discussion**

Drugs that activate 5-HT₂C receptors hold promise for the treatment of psychoses and psychostimulant abuse, in part because of their ability to modulate central dopamine signaling and their effectiveness in preclinical models and at least one clinical study (Di Matteo et al., 2004; Shen et al., 2010; Higgins et al., 2012; Cunningham et al., 2013). Herein is described (-)-MBP, a novel and potent 5-HT₂C receptor-specific agonist with 5-HT₂A and 5-HT₂C competitive antagonistic and inverse agonist properties that is effective in preclinical mouse models of psychoses, does not affect locomotion on its own, and reduces palatable food intake, important properties distinguishing it from available antipsychotic drugs that suppress locomotion and increase appetite, leading to obesity (Stip et al., 2012). In our present studies, (-)-MBP was compared directly with its enantiomer (+)-MBP, which has identical physiochemical properties but with a mirror image three-dimensional arrangement of atoms, to provide molecular support of successful 5-HT₂ receptor-mediated translation from cellular to behavioral potency and efficacy.
Relative to (+)-MBP, (-)-MBP showed considerably higher affinity at each of the [3H]antagonist-labeled 5-HT2 receptor subtypes in vitro, which paralleled its significantly enhanced behavioral potency and efficacy in vivo in the DOI-elicited HTR assay. Moreover, molecular determinants for function were found to differ between 5-HT2 subtypes: (+)-MBP activated 5-HT2A and 5-HT2B receptors as well as 5-HT2C receptors. The affinity of (-)-MBP at [3H]agonist-labeled human 5-HT2C receptors (9 nM Ki) was more than 9- and 20-fold higher than its affinity at [3H]agonist-labeled 5-HT2A and 5-HT2B receptors, respectively, providing evidence that (-)-MBP selectively stabilizes a high-affinity agonist conformation of the 5-HT2C receptor but not of the 5-HT2A or 5-HT2B receptors. Thus, a molecular basis for 5-HT2C-specific activation was established despite the relatively high (~75%) transmembrane sequence homology between 5-HT2 subtypes; the risks associated with 5-HT2A and/or 5-HT2B receptor activation can and should be avoided with regard to 5-HT2C-activating drugs.

(-)-MBP was a competitive antagonist of 5-HT activation of human 5-HT2A and 5-HT2B signaling and did not activate either receptor, even at 10 μM, which is 50- to 800-fold higher than its 5-HT2A/2B affinity values, depending on whether an agonist or antagonist is used to label the receptors. It is noteworthy that (-)-MBP was an inverse agonist at human 5-HT2B receptors, prospectively eliminating the possibility of 5-HT2B-mediated cardiac valvulopathy. Inverse agonism, however, was not observed consistently at human 5-HT2A

Fig. 4. (A) Both enantiomers of (-)-MBP dose-dependently attenuated the DOI-elicited HTR. (+)-MBP was more potent and efficacious than (-)-MBP, consistent with in vitro pharmacology data. Clozapine (CLOZ) also dose-dependently blocked the DOI-elicited HTR. Each data point represents the mean (± S.E.M.) of 5 to 7 subjects. All drug groups are significantly different from the DOI-only group (vehicle). (B) Pretreatment with (-)-MBP did not affect locomotion, but CLOZ and (+)-MBP significantly decreased locomotion relative to DOI (1 mg/kg). CLOZ also reduced locomotion compared with the group treated with vehicle (Veh) only; numbers on the x-axis refer to mg/kg dose. Bar graphs of locomotion (mean ± S.E.M.) are from representative groups shown in A. *Significantly different from DOI. #Significantly different from vehicle.

Fig. 5. (-)-MBP dose-dependently attenuated MK-801-elicited hyperactivity, similar to clozapine (CLOZ). Effects are shown for the total 60-minute session (bar graphs), and numbers on the x-axis refer to dose in mg/kg. Bar graphs represent the mean (± S.E.M.) of 6 (CLOZ groups) to 10 subjects. *Significantly different from MK-801 alone. Inset: Effects are plotted in 1-minute bins for the primary comparisons. Error bars in inset are excluded for clarity.

Fig. 6. Time course analysis of (-)-MBP (10 mg/kg). (-)-MBP administered 10 or 60 minutes before MK-801 significantly reduced MK-801-elicited hyperactivity. Effects are shown for the total 60-minute session (bar graphs). Bar graphs represent the mean (± S.E.M.) of 11 (vehicle) and 6 (for each of the remaining groups) subjects. *Significantly lower activity relative to MK-801 alone. Inset: Effects are plotted in 1-minute bins for the primary comparisons. Error bars in inset are excluded for clarity.
receptors, suggesting that (−)-MBP may be a 5-HT2A neutral antagonist. In summary, (−)-MBP is a potent 5-HT2C receptor-specific partial agonist that does not activate 5-HT2A or 5-HT2B receptors, setting it apart from all other reported selective 5-HT2C agonists, including the novel antiobesity drug Belviq, the widely used research agonist Ro60-0175 ([S]-2-(6-chloro-5-fluorindol-1-yl)-1-methylethylamine), and the prototypical agonist m-chlorophenylpiperazine (mCPP), all of which also activate 5-HT2A and 5-HT2B receptors. (−)-MBP was effective in several preclinical animal models of psychoses, including a model of 5-HT2-mediated hallucinations (DOI-elicited HTR), a model of dopamine hyperactivity (amphetamine-elicited hyperlocomotion), and a model of glutamate hypofunction (MK-801-elicited hyperlocomotion). Each of the targeted neurotransmitter systems associated with the animal models (i.e., 5-HT2A receptors, dopamine and norepinephrine transporter, and glutamate NMDA receptors, respectively) has been implicated in psychoses and schizophrenia, and drugs within each of these classes can mimic psychosis in humans (Aghajanian and Marek, 2000; Gonzalez-Maeso and Sealfon, 2009; Coyle et al., 2012; Masana et al., 2012), providing the models with some etiological validity. In these animal models, (−)-MBP was compared directly to the prototypical second-generation antipsychotic drug clozapine, which previously had been reported to attenuate the DOI-elicited HTR, and also amphetamine- and NMDA antagonist-induced hyperlocomotion (Corbett et al., 1995; Gleason and Shannon, 1997; Rojas-Corrales et al., 2007). (−)-MBP demonstrated similar efficacy as clozapine, although it was less potent. It is noteworthy that in contrast to clozapine, (−)-MBP did not compromise locomotion when administered alone, suggesting promise as an antipsychotic drug without liability for motoric disorders or sedation. However, we acknowledge that the aforementioned behavioral models are likely permissive and could lead to false-positive results; compounds effective in these models could potentially fail to ameliorate psychotic symptoms in humans, indicative that improved animal models for the core symptoms of schizophrenia are necessary (Brown et al., 2013).

All other reported 5-HT2C agonists that are effective as antipsychotic drugs, either in preclinical animal models or in clinical trials, also have 5-HT2A and/or 5-HT2B receptor agonist properties (Dunlop et al., 2005; Marquis et al., 2007; Siuciak et al., 2007; Rosenzweig-Lipson et al., 2012), raising the possibility that their therapeutic effects could be due to some combination of 5-HT2 subtype activation. However, we are not aware of any studies documenting antipsychotic activity of lorcaserin, the only FDA-approved 5-HT2C agonist that also activates 5-HT2A and 5-HT2B receptors (Thomsen et al., 2008). Meanwhile, (−)-MBP did not activate 5-HT2A or 5-HT2B receptors, which were expressed at relatively high densities in the transiently transfected HEK cells here and elsewhere (Booth et al., 2009); thus, the efficacy of (−)-MBP demonstrated in the rodent models of psychoses supports the assertion that 5-HT2C receptor activation alone or in combination with 5-HT2A and/or 5-HT2B antagonism or inverse agonism may negatively modulate psychotic behaviors. Finally, the results that (−)-MBP negatively modulates DOI-, amphetamine-, and MK-801-induced behaviors suggest that 5-HT2C agonism together with 5-HT2A/5-HT2B antagonism/inverse agonism may translate to optimal 5-HT2-based pharmacotherapy for behaviors associated with substance abuse (Cunningham et al., 2013).

Importantly, (−)-MBP did not alter locomotion when administered alone or in combination with DOI, MK-801, or amphetamine at behaviorally active doses (up to 10 mg/kg), indicating that its modulation of MK-801 and amphetamine-induced locomotion was not due to primary motor deficits. This effect has been noted for related trans-4-phenyl-2-dimethylaminotetralins (Canal et al., 2013; Morgan et al., 2013). In contrast, clozapine substantially decreased locomotion below levels of vehicle-treated animals when administered alone or in combination with DOI, mirroring its sedative
effects in humans, a side effect that may translate to the oft-reported “empty-headed” sensation caused by available antipsychotic drugs (Moritz et al., 2013). It is noteworthy that a recent paper reports that the hypolocomotion effect of clozapine, which is a 5-HT2A receptor inverse agonist of the canonical 5-HT2-C6 signaling pathway (Vanover et al., 2004), is mediated by 5-HT2A receptors (Williams et al., 2012). The affinity of clozapine and (−)MPB at rodent 5-HT2A receptors is very similar, suggesting that the inverse-agonist effects of clozapine and neutral-antagonist effects of (−)MPB at 5-HT2A receptors may translate to different behavioral outcomes or that the compounds are functionally selective regarding 5-HT2A signaling that affects locomotion. Alternatively, there may be an as yet undiscovered target(s) of (−)MPB that counterweights the hypolocomotion effect mediated by 5-HT2A receptors.

Also interesting regarding (−)MPB’s lack of effect on locomotion is that most 5-HT2C receptor agonists decrease locomotion in rodents (Fletcher et al., 2009; Halberstadt et al., 2010; Canal et al., 2013). Several reports show that 5-HT2C receptor-targeting compounds modulate the release of central dopamine, with agonists decreasing and antagonists or inverse agonists increasing dopamine release in an apparently neural system-dependent manner (Di Giovanni et al., 2011). The lack of effect on locomotor behavior with (−)MPB may be due to partial agonism of 5-HT2C receptors, which may dampen, for example, amphetamine-stimulated dopamine release but not cause a reduction in dopamine levels on its own. This phenomenon has been described with reference to dopamine D2 partial agonists, including the antipsychotic drug aripiprazole (Strange, 2008). Collectively, results indicate that (−)MPB may selectively negatively modulate psychostimulant-induced behaviors and not affect vigilance potentially translating to a drug that lacks sedative effects. Furthermore, the lack of effect of (−)MPB on locomotion in rodents suggests that it may treat psychoses without causing extrapyramidal side effects or catalepsy.

Other serious side effects of especially second-generation antipsychotic drugs include metabolic syndrome—specifically high glucose and cholesterol (Pramyothin and Khodhbar, 2010)—as well as increased appetite and weight gain leading to obesity (Stip et al., 2012). (−)MPB, in contrast, suppressed feeding in a mouse model of compulsive binge-eating/snack-food intake, suggestive of 5-HT2C agonism, which is known to decrease feeding and reduce weight in rodents and humans (Smith et al., 2010).

In summary, the novel 5-HT2C receptor-specific partial agonist (−)MPB displayed clear, favorable activity in animal models predictive of neuropsychiatric symptomology without possessing deleterious side effects associated with the administration of currently available antipsychotic medications, including alterations in motor activity and increased appetite. These results support further development of (−)MPB and other drug candidates with similar 5-HT2C agonism together with 5-HT2A/2B antagonism/inverse agonism for the treatment of psychoses and compulsive behavioral disorders involving substance (including food) abuse and addiction.

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References
Cheng Y and Prusoff WH (1973) Relationship between the inhibition constant (K_i) and the concentration of inhibitor which causes a 50% decrease in a reaction rate (I50) or an enzyme activity. Biochem Pharmacol 22:3099–3108.


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