Involvement of Sigma-1 Receptors in the Antidepressant-Like Effects of Dextromethorphan

Linda Nguyen
Matthew J. Robson
Jason R. Healy
Anna L. Scandinaro
Rae Reiko Matsumoto
*Touro University California, rae.matsumoto@tu.edu*

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**Recommended Citation**
Introduction

Depression affects up to one fifth of the world population, stands as the second leading cause of disability worldwide, and imposes a substantial economic burden [1,2]. In addition, the available pharmaceutical agents for treating depression are not effective in approximately a third of patients [3] and have a delayed clinical efficacy of several weeks to months [4]. Consequently, there is still a great need for faster acting and more effective treatments for depression.

Recently, a hypothesis was offered that dextromethorphan may have fast-acting antidepressant activity based on pharmacodynamic similarities to the N-methyl-D-aspartate (NMDA) antagonist ketamine [5]. In addition to binding to NMDA receptors, dextromethorphan binds to sigma-1 (σ₁) receptors, which are believed to be protein targets for a potential new class of antidepressant medications. The purpose of this study was to determine whether dextromethorphan elicits antidepressant-like effects and the involvement of σ₁ receptors in mediating its antidepressant-like actions. The antidepressant-like effects of dextromethorphan were assessed in male, Swiss Webster mice using the forced swim test. Next, σ₁ receptor antagonists (BD1063 and BD1047) were evaluated in conjunction with dextromethorphan to determine the involvement of σ₁ receptors in its antidepressant-like effects. Quinidine, a cytochrome P450 (CYP) 2D6 inhibitor, was also evaluated in conjunction with dextromethorphan to increase the bioavailability of dextromethorphan and reduce exposure to additional metabolites. Finally, saturation binding assays were performed to assess the manner in which dextromethorphan interacts at the σ₁ receptor. Our results revealed dextromethorphan displays antidepressant-like effects in the forced swim test that can be attenuated by pretreatment with σ₁ receptor antagonists, with BD1063 causing a shift to the right in the dextromethorphan dose response curve. Concomitant administration of quinidine potentiated the antidepressant-like effects of dextromethorphan. Saturation binding assays revealed that a Ki concentration of dextromethorphan reduces both the Kd and the Bmax of [3H] (+)-pentazocine binding to σ₁ receptors. Taken together, these data suggest that dextromethorphan exerts some of its antidepressant actions through σ₁ receptors.

Abstract

Dextromethorphan is an antitussive with a high margin of safety that has been hypothesized to display rapid-acting antidepressant activity based on pharmacodynamic similarities to the N-methyl-D-aspartate (NMDA) receptor antagonist ketamine. In addition to binding to NMDA receptors, dextromethorphan binds to sigma-1 (σ₁) receptors, which are believed to be protein targets for a potential new class of antidepressant medications. The purpose of this study was to determine whether dextromethorphan elicits antidepressant-like effects and the involvement of σ₁ receptors in mediating its antidepressant-like actions. The antidepressant-like effects of dextromethorphan were assessed in male, Swiss Webster mice using the forced swim test. Next, σ₁ receptor antagonists (BD1063 and BD1047) were evaluated in conjunction with dextromethorphan to determine the involvement of σ₁ receptors in its antidepressant-like effects. Quinidine, a cytochrome P450 (CYP) 2D6 inhibitor, was also evaluated in conjunction with dextromethorphan to increase the bioavailability of dextromethorphan and reduce exposure to additional metabolites. Finally, saturation binding assays were performed to assess the manner in which dextromethorphan interacts at the σ₁ receptor. Our results revealed dextromethorphan displays antidepressant-like effects in the forced swim test that can be attenuated by pretreatment with σ₁ receptor antagonists, with BD1063 causing a shift to the right in the dextromethorphan dose response curve. Concomitant administration of quinidine potentiated the antidepressant-like effects of dextromethorphan. Saturation binding assays revealed that a Ki concentration of dextromethorphan reduces both the Kd and the Bmax of [3H] (+)-pentazocine binding to σ₁ receptors. Taken together, these data suggest that dextromethorphan exerts some of its antidepressant actions through σ₁ receptors.


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* E-mail: rmatsumoto@hsc.wvu.edu

† Current address: Department of Pharmacology, Vanderbilt University School of Medicine, Nashville, Tennessee, United States of America
tions to modulate the activity of various ion channels and signaling molecules, including inositol triphosphates, protein kinases, and calcium [14,15].

Previous reports implicate $\sigma_1$ receptors as protein targets for existing and novel antidepressant drugs [10]. Currently marketed antidepressant drugs, such as tricyclic antidepressants, monoamine oxidase inhibitors, selective serotonin reuptake inhibitors (SSRIs), and newer generations of antidepressant drugs, bind to these receptors [10]. Earlier studies also demonstrate that $\sigma_1$ receptor agonists can modulate the activities of neurotransmitter systems, signaling pathways and brain regions implicated in the pathophysiology of depression [10] and that $\sigma_1$ receptor knockout mice exhibit a depressive-like phenotype [16].

The potential clinical relevance of these observations is further supported by reports that $\sigma_1$ receptor agonists produce antidepressant effects in experimental animals and humans [17,18,19,20,21,22]. Notably, the $\sigma_1$ receptor agonist igmesine hydrochloride proved to be as effective an antidepressant as the well-established SSRI fluoxetine in some clinical trials, though not in all cases [10,22]. Compared to existing medications, $\sigma_1$ receptor agonists may facilitate a more rapid onset of antidepressant efficacy [23]. Consistent with this, $\sigma_1$ receptor agonists such as $(\pm)$-pentazocine and SA 4503 can enhance serotonergic neuronal firing in the dorsal raphe nucleus after only two days of treatment, compared to the two weeks of treatment that is typically required of conventional antidepressant drugs [24,25].

In the studies herein, we test the hypothesis that dextromethorphan can exert antidepressant-like actions at least in part through $\sigma_1$ receptors. This activity may convey additional therapeutic advantages over ketamine under clinically relevant conditions since compared to ketamine which has micromolar affinity for $\sigma_1$ receptors [26], dextromethorphan exhibits nanomolar binding affinity for these receptors [9,27,28]. First, the ability of dextromethorphan to cause antidepressant-like effects was examined in the forced swim test. The forced swim test is the most validated behavioral assay for predicting antidepressant efficacy [3,29,30] and thus provides a rational format for the initial evaluation of the antidepressant potential of dextromethorphan. In addition, the effect of dextromethorphan on locomotor activity was measured to determine whether stimulant effects could account for its apparent antidepressant-like actions. The antidepressant drugs imipramine and fluoxetine were used as reference ligands for these behavioral tests. Second, to evaluate the potential involvement of $\sigma_1$ receptors in the in vivo antidepressant-like actions of dextromethorphan, pharmacological antagonists targeting $\sigma_1$ receptors were examined for their ability to prevent the antidepressant-like effects of dextromethorphan. Third, since dextromethorphan undergoes extensive first-pass metabolism by CYP2D6 to its major active metabolite dextorphan [11], the CYP2D6 inhibitor quinidine was administered concomitantly with dextromethorphan to raise the plasma concentration and bioavailability of dextromethorphan [12] and determine whether the metabolism of dextromethorphan affects its antidepressant efficacy. Finally, to define the manner in which dextromethorphan binds to $\sigma_1$ receptors (competitive and/or non-competitive), saturation binding studies were conducted.

Materials and Methods

Animals

Male, Swiss Webster mice (24–28 g; Harlan, Frederick, MD) were housed with food and water ad libitum, with a 12:12 h light–dark cycle. Animals were housed in groups of five for at least one week prior to initiation of experiments. All procedures were conducted in strict accordance with the recommendations in the Guide for the Care and Use of Laboratory Animals of the National Institutes of Health. The protocol was approved by the Institutional Animal Care and Use Committee at West Virginia University (Morgantown, WV), and all efforts were made to minimize suffering.

Drugs and Chemicals

Dextromethorphan hydrobromide and quinidine sulfate were provided by Avanir Pharmaceuticals, Inc. (Aliso Viejo, CA; for the behavioral studies) or purchased from Sigma-Aldrich (St. Louis, MO; for the binding assays). Imipramine hydrochloride was purchased from Sigma-Aldrich (St. Louis, MO). Fluoxetine hydrochloride, BD1063 [1-[2-(3,4-dichlorophenyl)ethyl]-4-methyl-piperazine díhydrochloride], and BD1047 [N-[2-(3,4-dichlorophenyl)ethyl]-N-methyl-2-(dimethylamino)ethylamine díhydrobromide] were obtained from Tocris (Ellisville, MO). [3H]$(\pm)$-Pentazocine (34.8 Ci/mmol) was procured from Perkin Elmer (Hopkington, MA). All other chemicals and reagents were purchased from standard commercial suppliers (Sigma-Aldrich, St. Louis, MO).

Drug Treatments

Mice ($N=5–15$/group) received intraperitoneal (i.p.) injections with the following treatments: (1) Saline; (2) Imipramine (10–20 mg/kg); (3) Fluoxetine (10–30 mg/kg); (4) Dextromethorphan (1–30 mg/kg); (5) BD1063 (3–30 mg/kg); (6) BD1047 (10–30 mg/kg); (7) BD1063 (10 mg/kg) + Imipramine (20 mg/kg); (8) BD1063 (10 mg/kg) + Dextromethorphan (10–50 mg/kg); (9) BD1047 (10–20 mg/kg) + Dextromethorphan (30 mg/kg); (10) Quinidine (30 mg/kg) + Saline; and (11) Quinidine (30 mg/kg) + Dextromethorphan (3–30 mg/kg). Treatment with quinidine was administered concurrently with saline or dextromethorphan. Treatment with a $\sigma_1$ receptor antagonist (BD1063 or BD1047) was administered 15 min prior to the second drug (imipramine or dextromethorphan).

Locomotor Activity

Locomotor activity was measured utilizing an automated activity monitoring system (San Diego Instruments, San Diego, CA). Prior to locomotor activity measurements, animals were acclimated to the testing facility for at least 30 min and habituated to the testing chambers for an additional 30 min. Each testing chamber consisted of a Plexiglas housing and a 16×16 photobeam array to detect lateral (ambulatory and fine) movements, with a separate 16 photobeam array to detect rearing activity. Subsequent to the acclimation period, animals were treated and placed back in their respective chambers. Ambulatory, fine and rearing movements were quantified and summed as a measure of total locomotor activity for the next 30 min.

Forced Swim Test

Immediately after the locomotor measurements, animals were placed in individual cylinders of water (10 cm deep) for a total of 6 min for the forced swim test. The initial 2 min was an acclimation period and not scored. During the remaining 4 min, immobility time was quantified using ANY-Maze Version 4.63 video tracking software (Stoelting Co., Wood Dale, IL). Immobility was defined as no activity other than that required to maintain the animal’s head above the surface of the water. ANY-Maze software settings were as follows: accustomization period = 120 s, test duration = 240 s, minimum immobility time = 2000 ms (2 s), and immobility sensitivity = 75%.
Saturation Binding Assays
To determine $K_d$ and $B_{max}$ by saturation binding, assays were performed in the absence (control) and presence of dextromethorphan (400 nM) using methods previously published in detail [31]. The concentration of dextromethorphan used in these assays was based on the reported $K_d$ of the drug for $\sigma_1$ receptors [27]. Briefly, 15 concentrations of $[^3]H$-pentazocine (0.1–100 nM) were used to label $\sigma_1$ receptors in P2 rat brain homogenates (400–500 μg/sample). Non-specific binding was determined in the presence of 10 μM haloperidol. Incubations occurred for 120 min at 25°C and membranes were washed 2–3 times using ice cold 10 mM Tris HCl, pH 8.0.

Data Analysis
Data from all experiments were analyzed using GraphPad Prism 5.0 (San Diego, CA). The behavioral data were analyzed by one-way analysis of variance (ANOVA) followed when applicable by post-hoc Dunnett’s or Tukey’s multiple comparison tests. The correlation between locomotor activity and immobility time was analyzed by Pearson’s r correlation test. The $K_d$ and $B_{max}$ were determined using nonlinear regression and analyzed by unpaired t-tests. For in vivo data, outliers (data points that were at least two standard deviations away from the mean) were excluded from analyses. Data are represented as mean ± S.E.M. P<0.05 was considered statistically significant for all data analyzed.

Results
Conventional Antidepressants Dose Response
The tricyclic antidepressant imipramine served as a positive control and significantly altered immobility time in the forced swim test (Figure 1A; $F[2,32] = 10.24, P<0.05$). Post-hoc Dunnett’s test showed that imipramine at 20 mg/kg significantly decreased immobility time when compared to saline ($q=4.52, P<0.001$). Imipramine did not alter locomotor activity, even at doses that produced antidepressant-like effects (Figure 1B; $F[2,30] = 0.23$, n.s.).

Consistent with earlier reports that the forced swim test does not reliably detect the effects of SSRIs [37], the SSRI fluoxetine did not significantly reduce immobility time in the forced swim test under the conditions used by our laboratory ($F[2,32] = 1.97$, n.s.). Fluoxetine also did not alter locomotor activity ($F[2,30] = 2.36$, n.s.).

Dextromethorphan Dose Response
Dextromethorphan significantly reduced immobility time (Figure 1C; $F[4,50] = 6.16, P<0.001$), with a post-hoc Dunnett’s test revealing that 30 mg/kg differed significantly from saline ($q = 4.70, P<0.05$). Dextromethorphan also produced significant effects on locomotor activity (Figure 1D; $F[4,48] = 4.27, P<0.05$), with post-hoc Dunnett’s tests confirming that the following doses of dextromethorphan elicited effects that differed significantly from the saline control: 1 mg/kg ($q = 2.63, P<0.05$) and 30 mg/kg ($q = 3.81, P<0.01$). Since dextromethorphan showed significant stimulant effects, a correlation analysis between locomotor activity and immobility time was carried out to determine whether stimulant effects could account for its apparent antidepressant-like actions. The Pearson’s r correlation test revealed that there was no correlation between the dextromethorphan-induced increase in locomotor activity and decrease in immobility time (Figure 1E; $r=-0.02$, n.s.)

Sigma-1 Receptor Antagonists Dose Response
When tested alone, the $\sigma_1$ receptor antagonist BD1063 displayed a significant effect on immobility time ($F[3,36]=4.11, P<0.05$). Post-hoc Dunnett’s tests showed that BD1063 significantly reduced immobility time at 30 mg/kg ($q = 3.41, P<0.01$), but not at 10 mg/kg ($q = 1.82$, n.s.). Consequently, all antagonist testing in the forced swim test was performed with the 10 mg/kg dose of BD1063 which did not have effects on its own. Alone, BD1063 also produced significant changes in locomotor activity ($F[3,34]=5.81, P<0.05$). Post-hoc Dunnett’s tests revealed that only the low 3 mg/kg, i.p. dose caused a significant increase in activity for BD1063 ($q = 2.73, P<0.05$), thereby indicating that the alterations in locomotor behavior did not account for the changes observed in the forced swim tests.

The second $\sigma_1$ receptor antagonist BD1047 alone displayed no significant effects in the forced swim test ($F[3,36]=2.55$, n.s.). In the locomotor studies, BD1047 produced an effect that significantly differed from saline injections ($F[3,34]=6.99, P<0.001$). Post-hoc Dunnett’s tests revealed that only the low 3 mg/kg, i.p. dose caused a significant increase in activity for BD1047 ($q = 3.70, P<0.01$).

Effects of Sigma Receptor Antagonists in the Presence of Dextromethorphan or Imipramine
Pretreatment of mice with behaviorally inactive (10 mg/kg) doses of BD1063 or BD1047, two well-established and selective $\sigma_1$ receptor antagonists, attenuated the antidepressant-like effects of dextromethorphan, but not imipramine (Figure 2). Pretreatment with BD1063 (10 mg/kg) attenuated the antidepressant-like effects of dextromethorphan (30 mg/kg) (Figure 2A). ANOVA confirmed a significant difference between the various treatment groups in the antidepressant study for dextromethorphan in the forced swim test ($F[3,41]=5.59, P<0.01$). Post-hoc Tukey’s multiple comparison tests revealed that the dextromethorphan alone treatment group differed significantly from saline ($q = 5.60, P<0.001$), as well as the BD1063 + Dextromethorphan group (Figure 2A; $q = 4.21, P<0.05$). Pretreatment of mice with BD1063 (10 mg/kg) also significantly decreased the locomotor stimulatory effect of dextromethorphan (30 mg/kg), with an overall significant difference between treatment groups ($F[3,39]=10.03, P<0.0001$). Moreover, post-hoc Tukey’s test confirmed that BD1063 treatment blocked the ability of dextromethorphan to increase locomotor activity ($q = 6.62, P<0.001$).

Pretreatment with the second $\sigma_1$ preferring antagonist BD1047 showed a trend toward the attenuation of the antidepressant-like effects of dextromethorphan (30 mg/kg), with the results of 10 mg/kg pretreatment with BD1047 illustrated in Figure 2B. The overall ANOVA was significant for the BD1047 pretreatment study ($F[5,64]=5.65, P<0.0005$). Pairwise comparisons using post-hoc Tukey’s multiple comparison tests further confirmed that the BD1047 (10 or 20 mg/kg) + Dextromethorphan groups did not differ significantly from saline ($q = 4.04$ and 2.77, n.s.). However, the differences in the effects of dextromethorphan in the absence and presence of BD1047 (10 or 20 mg/kg) were not significant ($q = 2.52$ and 3.07, n.s.), reflecting partial attenuation of the effects. In the locomotor studies, BD1047 significantly decreased the effects of dextromethorphan ($F[5,61]=6.39, P<0.0001$), with post-hoc Tukey’s tests confirming the ability of BD1047 (10 mg/kg) to block the stimulant effect of dextromethorphan (30 mg/kg) ($q = 5.41, P<0.05$).

In contrast to the attenuation of dextromethorphan-induced effects in the forced swim test, pretreatment with BD1063 did not prevent, although it non-significantly reduced, the antidepressant-like effects of imipramine (20 mg/kg) (Figure 2C). Post-hoc Tukey’s
Figure 1. Antidepressant-like effects of imipramine and dextromethorphan in the forced swim test in mice. Imipramine (0–20 mg/kg, i.p.) significantly decreased immobility time (A), but had no significant effects on locomotor activity (B). Dextromethorphan (0–30 mg/kg, i.p.) significantly decreased immobility time (C), and significantly increased locomotor activity (D). However, there was no correlation between dextromethorphan (30 mg/kg)-induced locomotor stimulatory effects and decreased immobility times (E). Data shown are expressed as mean ± S.E.M. *P<0.05, **P<0.01, ***P<0.001, compared with the saline-treated group; one-way ANOVA followed by post-hoc Dunnett's tests. Pearson's r correlation test for correlation analysis. IM, imipramine. DM, dextromethorphan.

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test confirmed that imipramine significantly reduced immobility time compared to saline ($q = 6.74, P < 0.001$). Post-hoc comparisons of the BD1063 + Imipramine group showed that its effects did not differ significantly from imipramine alone ($q = 2.00, \text{n.s.}$), and there was a significant reduction in immobility time compared to saline ($q = 4.55, P < 0.05$). Locomotor activity differed among the treatment groups ($F[3,39] = 5.49, P < 0.01$). Although imipramine and BD1063 at the doses tested did not differ from saline ($q = 1.01$ and 0.13, respectively, n.s.), the combination of BD1063 + Imipramine produced a significant decrease in locomotor activity ($q = 5.17, P < 0.01$).

**Effects of Sigma Antagonist BD1063 on Dextromethorphan Dose Response**

When testing a single dose of BD1063 (10 mg/kg) against different doses of dextromethorphan, the presence of BD1063 elicited a shift to the right in the dextromethorphan dose response curve (Figure 3A). However, the animals exhibited abnormal behaviors, particularly vocalization, during the locomotor tests beginning at the 50 mg/kg dose of dextromethorphan in combination with BD1063. Higher doses of dextromethorphan were lethal, which limited the extent to which the dose response could be characterized. In locomotor studies, when testing the single dose of BD1063 (10 mg/kg) against increasing doses of dextromethorphan, BD1063 appeared to block the dextromethorphan-induced locomotor activity (Figure 3B). However, as mentioned above, the testing of higher doses of dextromethorphan was not carried out due to behavioral toxicity.

**Effects of CYP2D6 Inhibitor Quinidine on Dextromethorphan Dose Response**

Concurrent administration of quinidine (30 mg/kg), which blocks the CYP2D6 metabolism of dextromethorphan [12], potentiated the antidepressant-like effect of dextromethorphan (10 mg/kg) (Figure 4A). ANOVA confirmed a significant difference between the various treatment groups ($F[7,77] = 8.45,$ [Image 58x354 to 540x730])
DM, dextromethorphan.

significant for the various treatment groups ($q= 6.96$, $P<0.001$). Post-hoc Tukey’s multiple comparison tests further confirmed that the dextromethorphan (30 mg/kg) alone treatment group differed significantly from saline ($q= 6.40$, $P<0.001$). In combination with quinidine, however, dextromethorphan had no significant stimulant effects ($q= 4.04$, n.s.). When tested alone, quinidine had no significant effects in the forced swim test ($t= 0.47$, n.s.) nor did it have any effect on locomotor activity ($t= 0.99$, n.s.).

**Dextromethorphan Binding to Sigma-1 Receptors**

The results of the $\sigma_1$ receptor saturation binding assays demonstrated there was a significant reduction in $K_d$ and $B_{\text{max}}$ when the assays were performed in the presence of dextromethorphan, compared to when no dextromethorphan was added to the assay (Table 1). Unpaired t-tests revealed a significant decrease in both $K_d$ ($t= 3.07$, $P<0.001$) and $B_{\text{max}}$ ($t= 4.29$, $P<0.005$) with the inclusion of 400 nM dextromethorphan in the assays.

Discussion

This study is the first to show that dextromethorphan has antidepressant-like effects *in vivo*, in addition to implicating $\sigma_1$ receptors as a mechanism contributing to its antidepressant actions. Moreover, concomitant administration of the CYP2D6 reversible inhibitor quinidine potentiated the effects of dextromethorphan in the forced swim test. This demonstrates that the antidepressant-like effects of dextromethorphan do not require conversion to the metabolite dextrorphan, and reveals dextromethorphan itself has antidepressant efficacy.

The antidepressant-like effects of dextromethorphan appear to involve $\sigma_1$ receptors. In the current study, two well-established $\sigma_1$ receptor antagonists (BD1063 and BD1047) reduced the antidepressant-like actions of dextromethorphan *in vivo*. They are thought to act in a competitive manner since in the presence of BD1063, the dose response curve for dextromethorphan was shifted to the right. An involvement of $\sigma_1$ receptors in the antidepressant-like effects of dextromethorphan is consistent with earlier reports that selective $\sigma_1$ receptor agonists can on their own reduce immobility time in the forced swim test [17,20,21,32] and produce antidepressant-like effects in other animal models such as the tail suspension test and olfactory bulbectomy [18,33]. Thus, additional studies involving these and other animal models used in depression research (e.g., sucrose preference test, novelty suppression) [3,29,30] will be needed in the future to further evaluate the antidepressant potential of dextromethorphan and the involvement of $\sigma_1$ receptors.

The ability of dextromethorphan to elicit antidepressant-like actions through $\sigma_1$ receptors suggests future studies to evaluate potential fast-acting therapeutic effects are also warranted. $\sigma_1$ Receptor agonists can enhance serotonergic neuronal firing in the dorsal raphe nucleus after only two days vs. two weeks of treatment that is typically required of conventional antidepressant drugs [24,25]. In addition, the fast-acting antidepressant drug ketamine has recently been shown to potentiate nerve growth factor (NGF)-induced neurite outgrowth through a $\sigma_1$-dependent mechanism [26], supporting the emerging importance of $\sigma_1$ receptors in modulating neuronal plasticity, which itself is a critical element for conveying both rapid and delayed antidepressant activity.

Earlier competition binding studies showed that dextromethorphan has significant affinity for $\sigma_1$ receptors (138–652 nM) [13,27,28,34], and thus further characterization of the interaction of dextromethorphan with $\sigma_1$ receptors was undertaken in the current study. The saturation binding studies indicate that the
interaction of dextromethorphan with $\sigma_1$ receptors is complex, with both a change in $B_{\text{max}}$ and $K_d$ in the binding of $[^3H] (+)$-pentazocine in the presence of dextromethorphan. The reduction in the number of $\sigma_1$ receptors ($B_{\text{max}}$) with which $[^3H] (+)$-pentazocine binds suggests non-competitive interactions of dextromethorphan with $\sigma_1$ receptors. However, there is also a decrease in $K_d$ for $[^3H] (+)$-pentazocine binding in the presence of dextromethorphan, suggesting additional competitive interactions. Together, the data support the presence of at least two distinct sites or modes of interaction with which dextromethorphan binds to the $\sigma_1$ receptor, one with which it has competitive interactions, and another with which it has non-competitive interactions. This interpretation would be consistent with other reports of multiple regions for ligand interactions on the $\sigma_1$ receptor, some of which have functional ramifications for agonist vs. antagonist activity [35,36,37]. The affinity differences of dextromethorphan for its

Table 1. Binding parameters for $\sigma_1$ receptors in the absence and presence of dextromethorphan.

<table>
<thead>
<tr>
<th>Assay condition</th>
<th>$K_d$ (nM)</th>
<th>$B_{\text{max}}$ (fmol/mg protein)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No additional compound</td>
<td>27.38±2.23</td>
<td>356±12</td>
</tr>
<tr>
<td>+ Dextromethorphan 400 nM</td>
<td>16.81±1.58</td>
<td>290±9</td>
</tr>
</tbody>
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Saturation binding assays in brain homogenates for $\sigma_1$ receptors were conducted using $[^3H] (+)$-pentazocine as the radioligand. The assays were performed in the absence or presence of dextromethorphan (400 nM). The $K_d$ and $B_{\text{max}}$ were determined using nonlinear regression. Dextromethorphan produced a significant decrease in $K_d$ and $B_{\text{max}}$. Data shown are expressed as mean ± S.E.M. *$p<0.05$, compared with $[^3H] (+)$-pentazocine alone; paired t-test. doi:10.1371/journal.pone.0089985.t001
two putative binding sites appear to be similar (<100-fold difference) since competition binding assays of dextromethorphan at $\sigma_1$ receptors are consistent with a one-site fit [27]. The antidepressant-like effects of dextromethorphan are thought to be mediated through the competitive binding site since i) there appears to be a rightward shift in its dose response curve in the forced swim test with no apparent change in maximal effect, and ii) (+)-pentazocine, the $\sigma_1$ agonist used to label the receptor, has previously also been reported to produce similar antidepressant-like effects [10,17].

In addition to interacting with $\sigma_1$ receptors, dextromethorphan has been reported to alter monoamine reuptake, particularly serotonin and norepinephrine at Ki values of 23 and 240 nM, respectively [38], which have implications for antidepressant effects in humans. The significant affinity of dextromethorphan for SERT (40 nM) [9] would be expected to contribute to antidepressant efficacy in humans, although it would not account for potential fast-acting effects, nor reductions in immobility time herein. Under the experimental parameters used in the current study, the classical SSRI fluoxetine did not produce significant reductions in immobility time in the forced swim test. This is consistent with the reports of others that the forced swim test does not reliably detect the antidepressant potential of SSRIs [39]. Thus, this mechanism, which is a known contributor to antidepressant efficacy in humans, is unlikely to account for the pattern of antidepressant-like effects observed with dextromethorphan herein. In contrast to its high affinity for SERT, dextromethorphan binds much more weakly with NET (>1 $\mu$M) [9], but its reported ability to modulate norepinephrine reuptake [38] would be expected to contribute conventional antidepressant effects under clinical conditions. Compared to the ability of BD1063 pretreatment to significantly block the antidepressant-like effects of dextromethorphan, it failed to attenuate that of imipramine, which has an overlapping binding profile with dextromethorphan: SERT (1.3–20 nM) [40,41,42,43], and $\sigma_1$ receptors (343 nM) [44]. This indicates that the $\sigma_1$ interaction may have a larger role in producing the antidepressant-like effects of dextromethorphan than that of imipramine. This is consistent with the wider range of protein targets through which imipramine, but not dextromethorphan, interacts, which include: serotonin 5-HT$_2$, muscarinic, and histamine H$_1$ receptors [9,43,46,47,48,49].

Finally, dextromethorphan elicits stimulant actions which were quantified herein as increases in locomotor activity. Two observations are of note with regard to these actions. First, the stimulant effects cannot account for the antidepressant-like actions of dextromethorphan. Second, quinidine enhances the antidepressant-like effects of dextromethorphan without producing an increase in locomotor activity. This suggests that addition of quinidine to dextromethorphan can be used clinically to optimize therapeutic antidepressant actions, without eliciting unwanted stimulant effects.

In conclusion, the data presented here show for the first time that dextromethorphan has antidepressant-like effects in an in vivo model and provide evidence that this effect occurs at least in part through a $\sigma_1$ receptor dependent mechanism. This is also the first report of the manner in which dextromethorphan interacts at the $\sigma_1$ receptor. Together with earlier studies and the potential of increasing dextromethorphan bioavailability by using the FDA- and EMA-approved dextromethorphan/quinidine formulation, these data suggest dextromethorphan should be further explored for translational potential as an antidepressant drug in clinical trials, as it may offer rapid-acting relief of depressive symptoms and the ability to resolve cases of treatment-resistant depression. In addition, further studies to understand the molecular and cellular mechanisms by which these effects occur are necessary and may yield important information about how various receptors, transporters and processes are involved in the ability of dextromethorphan to convey its antidepressant effects.

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Author Contributions
Conceived and designed the experiments: LN MJR RRM. Performed the experiments: LN MJR JRH ALS. Analyzed the data: LN MJR JRH ALS RRM. Wrote the paper: LN RRM. Edited the manuscript: LN MJR JRH ALS RRM.

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