Acute Effects of Brexpiprazole on Serotonin, Dopamine, and Norepinephrine Systems: An In Vivo Electrophysiologic Characterization

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ABSTRACT

Brexipiprazole, a compound sharing structural molecular characteristics with aripiprazole, is currently under investigation for the treatment of schizophrenia and depression. Using electrophysiological techniques, the present study assessed the in vivo action of brexpiprazole on serotonin (5-HT) receptor subtypes 5-HT1A, 5-HT1B, and 5-HT2A; dopamine (DA) D2 autoreceptors, and α1- and α2-adrenergic receptors. In addition, the effects on 5-HT1A autoreceptors in the dorsal raphe nucleus (DRN) and D2 autoreceptors in the ventral tegmental area (VTA) were compared with those of aripiprazole, an agent in wide clinical use. In the DRN, brexpiprazole completely inhibited the firing of 5-HT neurons via 5-HT1A agonism and was more potent than aripiprazole (ED50 = 230 and 700 μg/kg, respectively). In the locus coeruleus, brexpiprazole reversed the inhibitory effect of the preferential 5-HT2A receptor agonist DOI (2,5-dimethoxy-4-iodoamphetamine) on norepinephrine neuronal firing (ED50 = 110 μg/kg), demonstrating 5-HT2A antagonistic action. Brexpiprazole reversed the inhibitory effect of the DA agonist apomorphine on VTA DA neurons (ED50 = 61 μg/kg), whereas it was ineffective when administered alone, indicating partial agonistic action on D2 receptors. Compared with aripiprazole, which significantly inhibited the firing activity of VTA DA neurons, brexpiprazole displayed less efficacy at D2 receptors. In the hippocampus, brexpiprazole acted as a full agonist at 5-HT1A receptors on pyramidal neurons. Furthermore, it increased 5-HT release by terminal α2-adrenergic heteroreceptor but not 5-HT1B autoreceptor antagonism. In the lateral geniculate nucleus, brexpiprazole displayed α1B-adrenoceptor antagonistic action. Taken together, these results provide insight into the in vivo action of brexpiprazole on monoamine targets relevant in the treatment of depression and schizophrenia.

Introduction

Brexipiprazole (OPC-34712) is a compound currently under investigation for the treatment of depression and schizophrenia. Antipsychotic medications of the first and second generations are efficacious antagonists at dopamine (DA) D2 receptors. Indeed, D2 receptor antagonism is an effective strategy for treatment of positive symptoms in schizophrenia (Seeman and Lee, 1975; Rao and Remington, 2013). However, it is accompanied by unwanted motor side effects leading to extrapyramidal symptoms, at least in part by decreasing dopaminergic transmission in the striatum (Glazer, 2000; Kapur et al., 2000). These side effects are dampened when combined with antagonism of the serotonin (5-HT) receptor subtype 5-HT2A, a defining pharmacologic characteristic of second-generation antipsychotics (Stockmeier et al., 1993) that may be of therapeutic benefit in the treatment of both schizophrenia and mood disorders (Blier and Szabo, 2005; Kuroki et al., 2008).

Most second-generation antipsychotics have higher in vitro affinity for 5-HT2A than D2 receptors; brexpiprazole and aripiprazole are different in this regard (5-HT2A Ki = 0.47 and 4.7 nM and D2 Ki = 0.30 and 0.87 nM, respectively; Maeda et al., 2014b). Whereas most other atypical antipsychotics are D2 receptor antagonists, in vitro data indicate that brexpiprazole is a D2 partial agonist with lower intrinsic activity at D2 receptors than aripiprazole (Maeda et al., 2014b). Partial D2 receptor agonism is thought to have a buffering action on DA neurotransmission by stimulating D2 receptors under low DA conditions, while dampening their activation when DA levels are high (Burris et al., 2002). Indeed, in vivo systemic administration of aripiprazole has been shown to decrease the firing activity of ventral tegmental area (VTA) DA neurons to

ABBR EVIATIONS: AP, anterior/posterior; CA3, cornu ammonis layer 3; DA, dopamine; DOI, 2,5-dimethoxy-4-iodoamphetamine; DOS, duration of suppression of firing; DRN, dorsal raphe nucleus; DV, dorsal/ventral; 5-HT, serotonin; LC, locus coeruleus; LGN, lateral geniculate nucleus; M100907, (R)-(+)-α-(2,3-dimethoxyphenyl)-1-[2-(4-fluorophenyl)ethyl]-4-pipidinemethanol; ML, mediolateral; NE, norepinephrine; NET, norepinephrine transporter; 8-OHPDAT, 2-dipropylamino-8-hydroxy-1,2,3,4-tetrahydropalhalene; RL50, recovery time to 50% (of baseline firing); SERT, serotonin transporter; SNAPP089, 5-[(3,4-diphenyl-1-piperidinyl)propyl]amino]carbonyl]-1,4-dihydro-2,6-dimethyl-4-(4-nitrophenyl)-3-pyridinecarboxylic acid methyl ester hydrochloride; VTA, ventral tegmental area; WAY 100.635, N-[2-[4-(2-methoxyphenyl)-1-piperaziny]ethyl] N-[2-pyridyl]cyclohexanecarboxamide.
~70% of baseline, whereas complete inhibition of these neurons by the DA receptor agonist apomorphine was reversed by aripiprazole to a similar degree (Dahan et al., 2009). In contrast, acute haloperidol and clozapine administration increases firing of VTA DA neurons by D3 autoreceptor antagonism (Hand et al., 1987). Despite a different action on D3 autoreceptors, brexpiprazole improved behavioral measures predictive of antipsychotic efficacy, such as apomorphine-induced stereotypy and the conditioned avoidance response (Maeda et al., 2014a). Furthermore, brexpiprazole reduced head twitches induced by the preferential 5-HT2A receptor agonist DOI (2,5-dimethoxy-4-iodoamphetamine) and restored phenylcyclohexylinduced cognitive impairment to a greater extent than the 5-HT2A receptor antagonist M100907 ([R(+)-α-(2,3-dimethoxyphenyl)-1-[2-(4-fluorophenyl)ethyl]-4-pipidinemethanol], indicating in vivo antagonistic action at 5-HT2A receptors (Maeda et al., 2014a).

Aripiprazole and brexpiprazole are in vitro 5-HT1A receptor agonists (Kᵢ = 1.3 and 0.12 nM, respectively; Maeda et al., 2014b), a relevant pharmacologic characteristic in the treatment of mood disorders and schizophrenia (Blier and Ward, 2003; Newman-Tancredi, 2010). For aripiprazole, in vitro electrophysiology studies showed acute agonistic action at 5-HT1A autoreceptors in the dorsal raphe nucleus (DRN; Stark et al., 2007; Dahan et al., 2009). Interestingly, these autoreceptors were desensitized after only 2 days of aripiprazole administration (Chernoloz et al., 2009). Desensitization of 5-HT1A receptors could increase 5-HT neurotransmission, a common effect of long-term antidepressant administration thought to be therapeutically beneficial in the treatment of mood disorders (Blier and El Mansari, 2013). The recent demonstration that the restorative effect of both acute and chronic brexpiprazole on impaired cognitive function was lost by 5-HT1A receptor blockade further suggests in vivo 5-HT1A receptor agonism by this compound (Maeda et al., 2014a; Yoshimi et al., 2014).

Antagonism of α-adrenoceptors is a pharmacologic feature that may have therapeutic implications for schizophrenia and depression (Fawcett and Barkin, 1998; Arnsten, 2004; Marcus et al., 2010). In vitro, brexpiprazole has selective affinity for α1B-adrenoceptors (Kᵢ = 0.17 nM) over α1A (Kᵢ = 3.8 nM) and α1D (Kᵢ = 2.6 nM) subtypes (Maeda et al., 2014b). Furthermore, it may have antagonistic properties on α2-adrenoceptors (Maeda et al., 2014b), a pharmacologic characteristic known to increase neurotransmission of norepinephrine (NE) (Ghanbari et al., 2011; Chernoloz et al., 2012) and 5-HT (Mougeot et al., 1993; Haddjeri et al., 1998) by blockade of terminal α2-adrenergic autoreceptors and heteroreceptors, respectively.

Compared with aripiprazole, brexpiprazole has a 3- to 4-fold-higher in vitro affinity for the 5-HT transporter (SERT; IC₅₀ = 29 nM) and NE transporter (NET; IC₅₀ = 140 nM) (Maeda et al., 2014b). Blockade of these transporters is known to enhance 5-HT and NE neurotransmission (El Mansari et al., 2005; Chernoloz et al., 2012). As agents that block these transporters are currently first-line treatments for mood disorders, monoamine reuptake-blocking properties could contribute to the clinical efficacy of brexpiprazole.

To complement and extend insight into its action on therapeutically relevant targets, the present study used electrophysiologic techniques to determine the in vivo activity of brexpiprazole on 5-HT1A, 5-HT1B, 5-HT2A, and D2 Receptors, on α1- and α2-adrenoceptors, and on the SERT and NET.

**Materials and Methods**

**Animals.** Experiments were carried out in male Sprague-Dawley rats (Charles River Laboratories, St. Constant, QC, Canada) weighing 275–325 g housed under standard laboratory conditions (12-hour light/dark cycle with food and water ad libitum). In vivo extracellular unitary recordings were carried out in chloral hydrate–anesthetized rats (400 mg/kg i.p.) that were mounted in a stereotactic apparatus. Body temperature was maintained at 37°C throughout the experiment utilizing a thermistor-controlled heating pad. If applicable, prior to the electrophysiologic recordings, a catheter was inserted in a lateral tail vein for systemic intravenous injection of pharmacologic agents. At the end of experiments, animals were euthanized by a lethal dose of chloral hydrate (4% solution i.p.). All experiments were carried out in accordance with the Canadian Council on Animal Care and the local Animal Care Committee (University of Ottawa, Institute of Mental Health Research, Ottawa, ON, Canada).

**Compounds.** Brexpiprazole (200 µg/kg; Maeda et al., 2014b), aripiprazole (200 µg/kg), and the DA agonist apomorphine (40 µg/kg) were dissolved in a 0.5% lactic acid solution in distilled water; the pH of the solution was adjusted to 4.5 by addition of NaOH. The preferential 5-HT2A receptor agonist DOI (100 µg/kg), the α2-adrenoceptor agonist UK-143042 (10 and 400 µg/kg), and the 5-HT1a receptor agonist WAY 100,635 (N-[2-[(4-methylpiperidin-1-yl)methyl]N-(2-pyridyl)cyclohexanecarboxamide) were dissolved in distilled water. The selective α1a-adrenoceptor agonist (Wetzol et al., 1995) SNAP 5089 (5-[1-[3-(4,4-diphenyl-1-piperidinyl)propyl]amino]carbonyl]-1,4-dihydro-2,6-dimethyl-4-(4-nitrophenyl)-3-pyridinecarboxylic acid methyl ester hydrochloride; 1 mg/kg) was dissolved in 20% β-cyclodextrin in distilled water. Brexpiprazole and aripiprazole were provided by Lundbeck A/S (Valby, Denmark); all other compounds were purchased from Sigma-Aldrich (Oakville, ON, Canada).

**In Vivo Electrophysiologic Recordings.** Extracellular recordings of neurons in the VTA, DRN, and locus coeruleus (LC) were carried out with a single-barrel glass micropipette (Stoelting, Spencerville, MD) preloaded with 2 M NaCl and with impedance between 2 and 6 MΩ. Neurons in the cornu ammonis layer 3 (CA3) region of the hippocampus and lateral geniculate nucleus (LGN) were recorded with a five-barrel micropipette (impedances: central barrel, 2–5 MΩ; side barrels, 20–30 MΩ). The central barrel, used for unitary recordings, and one side barrel, used for automatic current balancing, were filled with 2 M NaCl; the other barrels were filled with brexpiprazole (1.2 M in distilled water and 0.5% lactic acid, pH 4.5), 5-HT (0.5 M in distilled 0.2 M NaCl, pH 4), NE bitartrate (10 mM in 0.2 M NaCl, pH 4), or quisqualic acid (1.5 M in 0.2 M NaCl, pH 4). 5-HT and NE were ejected as cations and retained with a negative current; quisqualate and brexpiprazole were ejected as anions (~3 to +3 nA and ~55 to ~90 nA, respectively) and retained with a positive current.

**Recording of DRN 5-HT Neurons.** Putative 5-HT neurons were recorded by positioning single-barrel glass micropipettes at the following coordinates (in millimeters from λ): anterior/posterior (AP), 1.0–1.2; mediolateral (ML), 0; and dorsal/ventral (DV), 5.0–7.0. At these coordinates, only neurons with a bi- or triphasic extracellular waveform with a long duration (0.8–1.2 milliseconds) positive phase and regular firing in the range of 0.8–2 Hz were recorded (Vandermaelen and Aghajanian, 1983).

**Recording of LC NE Neurons.** NE neurons were recorded by positioning single-barrel glass micropipettes at the following coordinates (in millimeters from λ): AP, ~1.0 to 1.2; ML, 1.0–1.3; and DV, 5.0–7.0. NE neurons were identified using the following criteria: regular firing rate (1–3 Hz), a long duration (0.8–1.2 milliseconds) of the rising phase of the action potential, and a brisk excitatory response followed by a short period of inhibition (~1 second) in reaction to a noxious pinch of the contralateral hind paw (Vandermaelen and Aghajanian, 1983). To test the effect of brexpiprazole on 5-HT2A receptors, NE neurons were inhibited by the preferential 5-HT2A receptor agonist DOI (100 µg/kg i.v.) (Szabo and Blier, 2001). Following a 60-second inhibition period, cumulative doses of brexpiprazole (50 and
100 μg/kg i.v.) were administered to reverse the inhibitory effect of DOI. The reversing effect of brexpiprazole was quantified relative to baseline firing activity.

Recording of VTA DA Neurons. Putative DA neurons were recorded by positioning single-barrel glass micropipettes at the following coordinates (in millimeters from λ): AP, 3.2–3.6; ML, 0.6–1.0; and DV, 7.0–9.0. At these coordinates, neurons with a long-duration (3–5 milliseconds) triphasic action potential with a marked negative deflection, an inflection or “notch” on the rising phase, an irregular spontaneous single-firing pattern (3–6 Hz), and slow bursting activity with decrementing action potential amplitude were recorded (Grace and Bunney, 1983). The start of a burst was defined as the occurrence of two spikes within 80 milliseconds; the end of a burst was defined as an interspike interval of >160 milliseconds (Grace and Bunney, 1984). Firing and burst activity was quantified relative to baseline, and values were obtained from the second half of a 120-second period after injection of pharmacologic agents. To test the effect of brexpiprazole on D2 autoreceptors, DA neurons were inhibited by the DA agonist apomorphine (40 μg/kg i.v.), which is known to produce a sustained suppression of firing on these neurons (Wang, 1981). Following a 60-second inhibition period, cumulative doses of brexpiprazole (25, 50, and 100 μg/kg i.v.) were administered to reverse the inhibitory effect of apomorphine. The reversing effect of brexpiprazole on firing rate was quantified relative to baseline firing activity.

Recording of Dorsal LGN Neurons. LGN neurons were recorded by positioning multibarrel micropipettes at the following coordinates (in millimeters from λ): AP, 3.8–4.2; ML, 4.0–4.2; and DV, 4.5–5.5. They were characterized by flashing light in the eye of the rat, which causes a brisk excitatory response in these neurons (Curet and de Montigny, 1988). LGN neurons are known to be excited by iontophoretic application of NE via activation of α1-adrenergic receptors (Rogawski and Aghajanian, 1980, 1982; Menkes et al., 1981). Because adrenoceptors of the 1B subtype are densely expressed in the dorsal LGN, whereas α1b-adrenoceptors are absent and there is minimal presence of α1a-adrenoceptors (Day et al., 1997), the LGN was chosen to assess the effect of brexpiprazole on α1a-adrenoceptors. Neuronal responsiveness to the iontophoretic application of NE before and after administration of brexpiprazole was assessed by determining the total number of spikes produced, corrected for baseline activity. Baseline activity was defined as the average firing rate 30 seconds pre- and post-ejection. For all data points, the average number of spikes excited was obtained by averaging the neural response to at least two consecutive injections of NE separated by an interval of at least 100 seconds.

Recording of Pyramidal Neurons in the CA3 Region of the Hippocampus. CA3 pyramidal neurons were recorded by positioning multibarrel micropipettes at the following coordinates (in millimeters from λ): AP, 3.8–4.2; ML, 4.0–4.2; and DV, 3.5–4.5. Because most CA3 pyramidal neurons are not spontaneously active in chloral hydrate–anesthetized rats, a small ejection current (1–2 ± 1 nA) was applied to the quisqualate barrel to activate them within their physiologic firing range (10–15 Hz) (Ranck 1973). The current and duration of 5-HT and NE ejection were kept constant before and after each intravenous injection of brexpiprazole. Neuronal responsiveness to the iontophoretic application of NE was assessed by determining the total number of spikes suppressed from start of ejection to recovery to 80% of baseline firing rate. Activity of the NET was assessed by determining the recovery time to 50% of the maximal inhibitory effect following a high-current ejection of NE (10–20 nA) and was expressed as RT50 (De Montigny et al., 1980). Neuronal responsiveness to 5-HT was assessed by determining the total number of spikes inhibited during a 50-second ejection divided by the ejection current of 5-HT (2–5 nA). Activity of the SERT was assessed by determining the time (in seconds) from the end of a 50-second ejection of 5-HT (20 nA) that fully inhibited the neurons to 50% recovery of baseline firing and was expressed as RT50 (Piaseyro et al., 1994). Partial or full agonism of brexpiprazole on 5-HT1A receptors was assessed by comparing the inhibitory effect of ejection of 5-HT alone to the inhibitory effect of concomitant ejection of 5-HT and brexpiprazole, following restoration of the firing rate to the same level as before ejecting brexpiprazole by increasing quissualate ejection. In this paradigm, coapplication of a partial agonist reduces the inhibitory effect of 5-HT, whereas coapplication of a full agonist does not change the inhibitory effect of 5-HT (Dong et al., 1998; Chhabra et al., 2010). To test whether the inhibitory effect of 5-HT and brexpiprazole was mediated by 5-HT1A receptors, the inhibitory effect of iontophoretic 5-HT and brexpiprazole application was compared before and after administration of the selective 5-HT1A receptor antagonist WAY 100.655 (100 μg/kg i.v.).

Electrical Stimulation of Afferent 5-HT Projections to Hippocampus. A bipolar electrode (NE-110; David Kopf, Tujunga, CA) was inserted at the following coordinates (in millimeters from λ): AP, 1.0; ML, 0.0; and DV, 7.8–8.2—to electrically stimulate 5-HT afferents while recording a CA3 pyramidal neuron using a multibarrel pipette (see above). A stimulator (S8800; Grass Technologies, Warwick, RI) was used to deliver 200 square pulses (0.5 millisecond, 1 or 5 Hz) at 300 μA. Duration of inhibition per stimulation was plotted in a peristimulus time histogram with a 2-millisecond bin size. The inhibitory effect of 5-HT fiber bundle stimulation on CA3 neurons was expressed as duration of suppression of firing (DOS; in milliseconds), defined as the period from the first bin showing a 50% reduction in the number of events per bin from the prestimulation value and the first subsequent bin attaining a 90% recovery of the number of events per bin from prestimulus values (Chaput et al., 1986). Electrical stimulation of 5-HT afferents causes endogenous release of 5-HT and briefly suppresses firing of CA3 pyramidal neurons by activating postsynaptic 5-HT1A receptors, an effect previously shown to be independent of 5-HT reuptake inhibition (Chaput et al., 1986). To determine the dose–response of brexpiprazole (25, 50, and 100 mg/kg i.v.) to reverse the decreasing effect on DOS of a high dose of the α2-adrenoceptor agonist clonidine (400 μg/kg i.v.). To validate this paradigm, a low dose of clonidine (10 μg/kg i.v.) was administered before the high dose of clonidine. Indeed, it is well established that a low dose of clonidine primarily activates α2-adrenergic autoreceptors on NE terminals, whereas coadministration of NE tone on α2-adrenoceptors located on 5-HT terminals, resulting in an increased DOS. A subsequent high dose of clonidine activates α2-adrenoceptors on 5-HT terminals, thereby producing a decrease in DOS (Mongeau et al., 1994). To determine the effect on the activity of terminal 5-HT1B autoreceptors, the effect of three doses of brexpiprazole (500 μg/kg i.v.) on the DOS following low- and high-frequency (1 and 5 Hz, respectively) stimulations in the same neuron was compared. Previous in vivo and in vitro studies showed that increasing the stimulation from 1 to 5 Hz results in greater activation of terminal 5-HT1B autoreceptors and, consequently, decreased 5-HT release. Therefore, a longer DOS following 1-Hz compared with 5-Hz stimulation is indicative of functional terminal 5-HT1B autoreceptors (Chaput et al., 1986; Blier et al., 1989).

Data Analysis/Statistics. Electrophysiologic recordings were made, and filtered from artifacts by waveform analysis, using Spike2 software version 6.17 (Cambridge Electronic Design, Cambridge, UK). Quantification of firing activity was performed using Spike2, with the exception of firing and burst analysis of VTA DA neurons, for which burstiDATor (https://github.com/nmo/burstiDATor) software was used. In experiments in which no competitive exogenous ligand was present, linear regression analysis was used to determine ED50 values and to compare the slope and intercept when comparing the effect of aripiprazole and brexpiprazole. In the presence of a competitive exogenous ligand, nonlinear curve fitting was used to obtain ED50 values. Experiments with <3 observations within the same subject were analyzed with a paired t test; experiments with ≥3 observations within the same subject were analyzed with repeated-measures analysis of variance followed by a Tukey post hoc test. All data were analyzed with GraphPad Prism version 5.01 (GraphPad Software, Inc., La Jolla, CA). Data are presented as mean ± S.E.M.; P < 0.05 was considered significant.
Results

Effect of Brexpiprazole and Aripiprazole on VTA DA Neurons. Brexpiprazole at cumulative doses of 200, 400, and 800 μg/kg did not significantly alter firing rate ($F_{1,39} = 3.15, n = 11, P = 0.083$; Fig. 1C) or bursting activity ($F_{1,29} = 1.61, n = 10, P = 0.21$; Fig. 1D) of VTA DA neurons from baseline activity. Aripiprazole, administered at these same doses, significantly decreased firing activity ($F_{1,22} = 11.93, n = 6, P = 0.0023$; Fig. 1C) and bursting activity of VTA DA neurons ($F_{1,18} = 7.58, n = 5, P = 0.013$; Fig. 1D). For an illustrative trace of the effect of brexpiprazole and aripiprazole, see Fig. 1, A and B, respectively.

Effect of Brexpiprazole on D2 Autoreceptors on VTA DA Neurons. Following a 60-second inhibition period of putative DA neurons in the VTA by the DA receptor agonist apomorphine (40 μg/kg i.v.), brexpiprazole administration (25–100 μg/kg) reversed the effect of apomorphine to ~65% of baseline firing. Sigmoidal curve fitting ($n = 9$) yielded an ED$_{50}$ value of 61 μg/kg for brexpiprazole on this effect (Fig. 2B; for an illustrative trace, see Fig. 2A).

Effect of Brexpiprazole and Aripiprazole on 5-HT$_{1A}$ Autoreceptors. In the DRN, brexpiprazole at cumulative doses of 100 and 200 μg/kg inhibited the firing of 5-HT

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Fig. 1. Effect of systemic brexpiprazole and aripiprazole administration on VTA DA neurons. (A and B) Illustrative trace of DA neurons and response to intravenous administration of brexpiprazole (A, black arrows) and aripiprazole (B, gray arrows). (C and D) Brexpiprazole ($n = 11$) did not change firing activity of VTA DA neurons, whereas aripiprazole ($n = 6$) significantly reduced both firing and bursting activity of these neurons. Data were analyzed using linear regression and are presented as mean ± S.E.M. Aripiprazole had a significant effect in comparison with saline administration. **$P < 0.01$ for slope; ***$P < 0.01$ for intercept.

Fig. 2. Effect of systemic brexpiprazole administration on VTA DA neurons inhibited by the dopamine agonist apomorphine. (A) Illustrative trace of a DA neuron and response to intravenous administration of apomorphine and brexpiprazole. (B) Brexpiprazole reversed the inhibitory effect of apomorphine ($n = 9$). The ED$_{50}$ value was obtained with a sigmoidal curve fit; data are presented as mean ± S.E.M.
neurons \((n = 11)\), an effect not reversed by administration of the NE reuptake inhibitor desipramine \((5 \text{ mg/kg})\), whereas the selective 5-HT\(_{1A}\) receptor antagonist WAY 100.635 reversed this inhibition \((n = 3)\); for an illustrative trace, see Fig. 3A). Similarly, an inhibitory effect of aripiprazole was observed on 5-HT neurons \((n = 15)\) that was reversed by WAY 100.635 but not desipramine \((n = 3)\). For aripiprazole, the experiment was initially conducted by administering cumulative doses of 200 \(\mu\text{g/kg}\) \((n = 6)\), based on a previous study (Dahan et al., 2009). As the inhibitory effect of these injections did not fully inhibit 5-HT neurons up to a cumulative dose of 600 \(\mu\text{g/kg}\), aripiprazole was administered at 500 \(\mu\text{g/kg}\) \((n = 9)\) in a subsequent experiment. Data from these experiments were pooled, as statistical analysis demonstrated that the dose-responsiveness of 5-HT neurons to aripiprazole at increments of 200 and 500 \(\mu\text{g/kg}\) was not different (slope: \(F_{1,45} = 0.04, P > 0.05\); intercept: \(F_{1,46} = 0.08, P > 0.05\)). Statistical analysis demonstrated a significantly lower ED\(_{50}\) value for brexpiprazole than for aripiprazole \((230 \text{ and } 700 \mu\text{g/kg}, \text{respectively}; F_{1,78} = 31.51, P < 0.0001; \text{Fig. 3B}).

**Effect of Brexpiprazole on Postsynaptic 5-HT\(_{1A}\) Receptors.** In the hippocampus, systemic administration of brexpiprazole up to a dose of 1500 \(\mu\text{g/kg}\) did not change the number of spikes suppressed per nanoampere following iontophoretic application of 5-HT on CA3 pyramidal neurons \((F_{1,30} = 2.72, P > 0.05; \text{data not shown}).

Iontophoretic application of both brexpiprazole and 5-HT had an inhibitory effect on CA3 pyramidal neurons \((n = 12;\) for an illustrative trace, see Fig. 4A). When brexpiprazole and 5-HT were ejected concomitantly, the neuronal inhibition of CA3 pyramidal neurons did not differ from when 5-HT was ejected alone \((P > 0.05, n = 12; \text{Fig. 4D}).\) This inhibitory effect of both agents was significantly dampened after systemic administration of WAY 100.635 \((P < 0.05 \text{ and } P < 0.01, \text{respectively}; \text{Fig. 4, B and C}).

**Effect of Brexpiprazole on the SERT.** In the hippocampus, the RT\(_{50}\) value (a measure for SERT activity) following iontophoretic application of 5-HT on CA3 pyramidal neurons was not changed by administration of brexpiprazole up to a dose of 1500 \(\mu\text{g/kg}\) \((F_{1,32} = 0.47, P > 0.05; \text{data not shown}).

**Effect of Brexpiprazole on Terminal 5-HT\(_{1B}\) Autorceptors.** The DOS produced on the same neuron by electrical stimulation of 5-HT afferents with stimulation frequencies of 1 and 5 Hz was increased by brexpiprazole at doses of 500, 1000, and 1500 \(\mu\text{g/kg}\) \((\text{Fig. 7B}).\) For 5-Hz stimulations, the corresponding DOS at these doses were 38 ± 3, 48 ± 5, and 49 ± 4, while the DOS at baseline was 27 ± 2 milliseconds. Statistical analysis demonstrated that under control conditions and after cumulative doses of brexpiprazole, the DOS after 1-Hz stimulation remained significantly greater than the DOS after 5-Hz stimulation (slope: \(F_{1,36} = 0.91, P > 0.05; \text{intercept: } F_{1,37} = 13.96, P = 0.0006).\)

**Effect of Brexpiprazole on 5-HT\(_{2A}\) Receptors in the LC.** Following a 60-second inhibition period of NE neurons in the LC by the 5-HT\(_{2A}\) agonist DOI \((100 \mu\text{g/kg i.v.})\), brexpiprazole administration \((50–400 \mu\text{g/kg})\) reversed NE
neural firing to ~80% of baseline firing, with an ED$_{50}$ value estimated at 110 $\mu$g/kg (Fig. 5B; for an illustrative trace, see Fig. 5A).

Effect of Brexpiprazole on Postsynaptic $\alpha_{1B}$-Adrenoceptors in the LGN. In the LGN, acute administrations of brexpiprazole at a dose of 500 and 1000 $\mu$g/kg significantly decreased the excitatory action of exogenous NE on LGN neurons by 44% and 77%, respectively ($F_{2,55} = 20.10; P = 0.0034$, and $P < 0.001$ for these respective doses; Fig. 6B), with an ED$_{50}$ value estimated at 630 $\mu$g/kg. The excitatory effect of NE ejection was not changed by prior administration of the $\alpha_{1A}$-adrenoceptor antagonist SNAP 5089 (1 mg/kg i.v.), whereas brexpiprazole administration still decreased neuronal excitability in the LGN after SNAP 5089 administration ($n = 2$; for an illustration, see Fig. 6A).

Effect of Brexpiprazole on Postsynaptic $\alpha_{2}$-Adrenoceptors. In the hippocampus CA3 region, systemic administration of brexpiprazole up to a dose of 1500 $\mu$g/kg did not change the number of spikes inhibited per nanoampere following iontophoretic application of NE on pyramidal neurons ($F_{1,28} = 0.95, P > 0.05$; data not shown).

Effect of Brexpiprazole on the NET. In the hippocampus CA3 region, the RT$_{50}$ value following iontophoretic application of NE on CA3 pyramidal neurons was not changed by administration of brexpiprazole up to a dose of 1500 $\mu$g/kg ($F_{1,30} = 0.01, P > 0.05$; data not shown).

Effect of Brexpiprazole on Terminal $\alpha_{2}$-Adrenoceptors on 5-HT Terminals. Clonidine at a dose of 10 $\mu$g/kg significantly increased the DOS value following 1-Hz stimulation compared with baseline, an effect completely reversed by a subsequent injection of clonidine at a dose of 400 $\mu$g/kg ($F_{3,5} = 13.63, n = 6, P < 0.0001$; Fig. 7A). Following these doses of clonidine, the DOS increased with cumulative administration of brexpiprazole (500, 1000, and 1500 $\mu$g/kg i.v.) in a dose-dependent fashion (Tukey post hoc test, $P < 0.01$, $P < 0.001$, and $P < 0.001$ for these doses, respectively). Administration of brexpiprazole alone also increased the DOS value in a dose-dependent manner ($F_{3,4} = 4.16, n = 5, P = 0.02$; Fig. 7B). Tukey post hoc testing revealed a significant effect of brexpiprazole on DOS at a dose of 1000 and 1500 $\mu$g/kg ($P < 0.01$ and $P < 0.01$, respectively). Clonidine administration (10 and 400 $\mu$g/kg) had no altering effect on the
DOS when it was administered after brexpiprazole ($P > 0.05$; Fig. 7B).

**Discussion**

**Brexiprazole: Effect on VTA DA Neurons.** Brexipiprazole reversed the inhibitory action of the DA receptor agonist apomorphine on neural firing of VTA DA neurons, thus demonstrating antagonistic action at $D_2$ autoreceptors (Fig. 2). Interestingly, brexpiprazole by itself did not significantly change the firing rate or bursting activity of DA neurons (Fig. 1). In contrast, the classic $D_2$ receptor antagonist haloperidol is known to increase firing and burst activity of VTA DA neurons when administered acutely, an effect attributable to blockade of endogenous DA inhibitory tone on $D_2$ autoreceptors (Pucak and Grace, 1994). Because brexpiprazole did not alter firing and bursting activity of VTA DA neurons when administered acutely, an effect attributable to blockade of endogenous DA inhibitory tone on $D_2$ autoreceptors, brexpiprazole reversed neuronal inhibition of VTA DA neurons by apomorphine, although less potently (Dahan et al., 2009). In the present study, aripiprazole significantly reduced the firing and bursting activity of VTA DA neurons to a similar degree as reported previously (Fig. 1; Dahan et al., 2009). The difference in effects on DA neurons of aripiprazole and brexpiprazole is likely due to a lower intrinsic activity of the latter agent at $D_2$ receptors, in line with their in vitro profiles (Maeda et al., 2014b). Notably, the present study also demonstrated more potent in vivo agonism of brexpiprazole on 5-HT1A receptors than aripiprazole (discussed below). Because activation of prefrontal 5-HT1A receptors is known to excite VTA DA neurons (Arborelius et al., 1993; Díaz-Mataix et al., 2005; Gronier, 2008), a difference in degree of 5-HT1A receptor agonism could contribute to the distinct effects of brexpiprazole and aripiprazole on the firing activity of DA neurons.

**Brexiprazole: Effect on the 5-HT System.** Brexipiprazole dose-dependently decreased the firing rate of 5-HT neurons in the DRN (Fig. 3). This inhibitory effect was due to agonism at 5-HT1A receptors on these neurons, as the selective 5-HT1A receptor antagonist WAY 100.635, but not the NE reuptake inhibitor desipramine, reversed the inhibitory action of brexpiprazole (Fig. 3A). Compared with aripiprazole, brexpiprazole was significantly more potent at activating 5-HT1A autoreceptors (Fig. 3B), a finding in line with the in
vivo affinity for 5-HT$_{1A}$ receptors of these agents (Maeda et al., 2014b). To the best of our knowledge, two previous studies assessed the dose-dependent effect of aripiprazole to inhibit DRN 5-HT neurons; Dahan et al. (2009) reported an ED$_{50}$ value of 540 mg/kg, in close similarity to the present findings, while the ED$_{50}$ for aripiprazole in the work by Stark et al. (2007) is estimated at 200–250 mg/kg. The reason for this difference remains to be established, although linear versus logarithmic dose-response estimation could play a role.

In the hippocampus, the activity of the SERT, assessed using the RT$_{50}$ index, remained unaltered following brexpiprazole administration up to a dose of 1500 µg/kg, whereas drugs that occupy SERT to a significant extent in vivo are known to prolong the RT$_{50}$ index (Piñeyro et al., 1994; Ghanbari et al., 2010). Microiontophoretic application of brexpiprazole and 5-HT both inhibited CA3 pyramidal neurons (Fig. 4, A and C), an effect attributable to 5-HT$_{1A}$ activation. Indeed, the inhibitory effect of these agents was blocked after systemic administration of WAY 100.635 (Fig. 4, B and C). Importantly, the inhibitory effect of 5-HT alone was unaltered when brexpiprazole was coejected (Fig. 4D). This absence of competitive action on 5-HT$_{1A}$ receptors of brexpiprazole with 5-HT indicates that brexpiprazole acted as a full 5-HT$_{1A}$ receptor agonist in vivo. Indeed, previous studies using the same paradigm showed full agonistic action of BAY 3702 (Dong et al., 1998) and trazodone (Ghanbari et al., 2010), whereas 8-OHDPAT (2-dipropylamino-8-hydroxy-1,2,3,4-tetrahydronaphthalene; Hadrava et al., 1996), gepirone (Hadrava et al., 1995), and asenapine (Ghanbari et al., 2009) acted as partial agonists at 5-HT$_{1A}$ receptors in the hippocampus.

Brexpiprazole administration dose-dependently increased the DOS following electrical stimulations of 5-HT afferents at 1 Hz (Fig. 7B), an effect that could theoretically be attributable...
Acute Brexpiprazole and Monoamines

The present results show acute in vivo action of brexpiprazole at all three monoamine (5-HT, NE, and DA) systems. Similarly to aripiprazole, brexpiprazole acted as a partial D₂ receptor agonist in vivo but is relatively less efficacious at this receptor subtype. Clinically, D₂ receptor partial agonism is thought to buffer fluctuations in DA transmission (Burriss et al., 2002; Shapiro et al., 2003), in line with the behavioral effects of brexpiprazole in animal models of schizophrenia (Maeda et al., 2014a). Furthermore, the potent in vivo agonistic action of brexpiprazole on 5-HT₁A receptors could be a relevant pharmacologic feature in treatment of both mood disorders and schizophrenia (Blier and Ward, 2003; Newman-Tancredi, 2010). Acute brexpiprazole administration reduced inhibition of two important interaction nodes between the 5-HT and NE systems. First, it blocked...
5-HT\textsubscript{2A} receptors, a receptor type that dampens LC NE firing when 5-HT neurotransmission is enhanced (Dremencov et al., 2007; Chernoloz et al., 2009). Second, brexpiprazole blocked α\textsubscript{2}-adrenoceptors on 5-HT\textsubscript{3} terminals, a receptor type that dampens 5-HT release when NE neurotransmission is elevated (Mongeau et al., 1993). As the therapeutic effect of potent 5-HT\textsubscript{2A} receptor antagonist in combination with 5-HT reuptake inhibitors is well recognized (Nelson and Papakostas, 2009), the present data support the use of brexpiprazole as an augmentation strategy. This notion is strengthened by the recent demonstration of clinical efficaciousness of brexpiprazole as an adjunct to antidepressants in major depressive disorder (Thase et al., 2014). In addition, combined but not separate administration of brexpiprazole and NE or 5-HT reuptake inhibitors had an antidepressant-like effect in rodents (Hirose et al., 2014).

Following this in vivo pharmacologic characterization, and because brexpiprazole will be administered on a long-term basis in the clinic, it will be crucial to investigate the effect of sustained brexpiprazole administration on therapeutically relevant monoamine targets.

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Authorship Contributions

**Participated in research design:** Oosterhof, El Mansari, Blier.

**Conducted experiments:** Oosterhof.

**Performed data analysis:** Oosterhof.

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