1. Title page

Acute effects of brexipiprazole on serotonin, dopamine, and norepinephrine systems: an in vivo electrophysiological characterization

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2. Running title page

a) Running title: Acute brexpiprazole and monoamines

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d) A list of non-standard abbreviations
5-HT     Serotonin
8-OH-DPAT 2-dipropylamino-8-hydroxy-1,2,3,4- tetrahydronaphthalene
AP       Anterior/posterior
Brex     Brexpiprazole
CA3      Cornu Ammonis layer 3
Clo      Clonidine
DA       Dopamine
DOI      2,5-dimethoxy-4-iodoamphetamine
DOS      Duration of silence
DRN      Dorsal raphe nucleus
DV       Dorsal/ventral
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<th>Acronym</th>
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<td>i.v.</td>
<td>Intravenous</td>
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<td>LC</td>
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<td>LGN</td>
<td>Lateral geniculate nucleus</td>
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<td>Mediolateral</td>
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<td>Norepinephrine transporter</td>
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<td>PCP</td>
<td>Phencyclidine</td>
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<td>RT&lt;sub&gt;50&lt;/sub&gt;</td>
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e) Recommended section assignment: Neuropharmacology
3. Abstract

Brexpiprazole, 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)\textsubscript{1A}, 5-HT\textsubscript{1B}, 5-HT\textsubscript{2A} receptor subtypes, dopamine (DA) D\textsubscript{2} autoreceptors, and α\textsubscript{1}- and α\textsubscript{2}-adrenergic receptors. In addition, the effects on 5-HT\textsubscript{1A} autoreceptors in the dorsal raphe nucleus (DRN) and D\textsubscript{2} autoreceptors in the ventral tegmental area (VTA) were compared to those of aripiprazole, an agent in wide clinical use. In the DRN, brexpiprazole completely inhibited the firing of 5-HT neurons via 5-HT\textsubscript{1A} agonism, and was more potent than aripiprazole (ED\textsubscript{50}=230 and 700 μg/kg, respectively). In the locus coeruleus, brexpiprazole reversed the inhibitory effect of the preferential 5-HT\textsubscript{2A} receptor agonist DOI on norepinephrine neuronal firing (ED\textsubscript{50}=110 μg/kg), demonstrating 5-HT\textsubscript{2A} antagonistic action. Brexpiprazole reversed the inhibitory effect of the DA agonist apomorphine on VTA DA neurons (ED\textsubscript{50}=61 μg/kg), whereas it was ineffective when administered alone, indicating partial agonistic action on D\textsubscript{2} receptors. Compared to aripiprazole, which significantly inhibited the firing activity of VTA DA neurons, brexpiprazole displayed less efficacy at D\textsubscript{2} receptors. In the hippocampus, brexpiprazole acted as a full agonist at 5-HT\textsubscript{1A} receptors on pyramidal neurons. Furthermore, it increased 5-HT release by terminal α\textsubscript{2}-adrenergic heteroreceptor, but not 5-HT\textsubscript{1B} autoreceptor antagonism. In the lateral geniculate nucleus, brexpiprazole displayed α\textsubscript{1B}-adrenoceptor antagonistic action. Taken together, these results provide insight in the in vivo action of brexpiprazole on monoamine targets relevant in the treatment of depression and schizophrenia.
4. Introduction

Brexpiprazole (OPC-34712) is a compound currently under the investigation for the treatment of depression and schizophrenia. Antipsychotic medications from the first and second generation are efficacious antagonists at dopamine (DA) D_2 receptors. Indeed, D_2 receptor antagonism is the 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 serotonin (5-HT)_{2A} receptors antagonism, a defining pharmacological 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-HT_{2A} than D_2 receptors; brexpiprazole and aripiprazole are different in this regard (5-HT_{2A} K_i=0.47 and 4.7 nM; D_2 K_i=0.30 and 0.87 nM, respectively; Maeda, Sugino, et al., 2014). Whereas most other atypical antipsychotics are D_2 receptor antagonists, in vitro data indicates that brexpiprazole is a D_2 partial agonist with lower intrinsic activity at D_2 receptors than aripiprazole (Maeda, Sugino, et al., 2014). Partial D_2 receptor agonism is thought to have a buffering action on DA neurotransmission by stimulating D_2 receptors under low DA conditions, while dampening their activation when DA levels are high (Burris, 2002). Indeed, in vivo systemic administration of aripiprazole has been shown to decrease the firing activity of ventral tegmental area (VTA) DA neurons to approximately 70% of baseline, whereas complete inhibition of these neurons by the DA 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 D_2 autoreceptors antagonism (Hand et al., 1987). Despite a different action on D_2 autoreceptors, brexpiprazole improved behavioral measures predictive for antipsychotic efficacy, such as apomorphine-induced stereotypy and the conditioned avoidance response (Maeda, Lerdrup, et al., 2014). Furthermore, brexpiprazole reduced
head-twitches induced by the preferential 5-HT$_{2A}$ receptor agonist DOI and restored phencyclidine (PCP)-induced cognitive impairments to greater extent than the 5-HT$_{2A}$ receptor antagonist M100907, indicating in vivo antagonistic action at 5-HT$_{2A}$ receptors (Maeda, Lerdrup, et al., 2014).

Aripiprazole and brexpiprazole are in vitro 5-HT$_{1A}$ receptor agonists (Ki=1.3 and 0.12 nM, respectively; Maeda, Sugino, et al., 2014), a relevant pharmacological characteristic in treatment of mood disorders and schizophrenia (Blier and Ward, 2003; Newman-Tancredi, 2010). For aripiprazole, in vivo electrophysiology studies showed acute agonistic action at 5-HT$_{1A}$ autoreceptors in the dorsal raphe nucleus (DRN; Stark et al., 2007; Dahan et al., 2009). Interestingly, these autoreceptors were desensitized after only 2-day aripiprazole administration (Chernoloz et al., 2009). Desensitization of 5-HT$_{1A}$ 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-HT$_{1A}$ receptor blockade further suggests in vivo 5-HT$_{1A}$ receptor agonism by this compound (Maeda, Lerdrup, et al., 2014; Yoshimi et al., 2014).

Antagonism of $\alpha$-adrenoceptors is a pharmacological 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 $\alpha_{1B}$-adrenoceptors (Ki = 0.17 nM) over $\alpha_{1A}$ (Ki = 3.8 nM) and $\alpha_{1D}$-subtypes (Ki = 2.6 nM; Maeda, Sugino, et al., 2014). Furthermore, it may have antagonistic properties on $\alpha_2$-adrenoceptors (Maeda, Sugino, et al., 2014), a pharmacological characteristic known to increase neurotransmission of NE (Ghanbari et al., 2011; Chernoloz et al., 2012) and 5-HT (Mongeau et al., 1993; Haddjeri et al., 1998) by blockade of terminal $\alpha_2$-adrenergic autoreceptors and -heteroceptors, respectively.

Compared to aripiprazole, brexpiprazole has a 3-4 fold higher in vitro affinity for the serotonin transporter (SERT; IC$_{50}$=29 nM) and norepinephrine transporter (NET; IC=140 nM; Maeda, Sugino, et al., 2014). 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 in treatment of mood
disorders, monoamine reuptake blocking properties could contribute to the clinical efficacy of brexpiprazole.

To complement and extend insight in its action on therapeutically relevant targets, the present study used electrophysiological techniques to determine the \textit{in vivo} activity of brexpiprazole on 5-HT\textsubscript{1A}, 5-HT\textsubscript{1B}, 5-HT\textsubscript{2A} and D\textsubscript{2} receptors, \(\alpha\textsubscript{1}\) - and \(\alpha\textsubscript{2}\)-adrenoreceptors, and on the SERT and NET.
5. Methods

Animals

Experiments were carried out in male Sprague-Dawley rats (Charles River, St. Constant, QC, Canada) weighing 275-325 g housed under standard laboratory conditions (12:12 light-dark cycle with food and water ad libitum). In vivo extracellular unitary recordings were carried out in chloral hydrate anaesthetized rats (400 mg/kg; i.p.) that were mounted in a stereotaxic apparatus. Body temperature was maintained at 37 °C throughout the experiment utilizing a thermistor-controlled heating pad. If applicable, prior to the electrophysiological recordings a catheter was inserted in a lateral tail vein for systemic intravenous (i.v.) 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, Ontario, Canada).

Compounds

Brexpiprazole (Maeda, Sugino, et al., 2014; 200 μg/kg), aripiprazole (200 μg/kg) and the DA agonist apomorphine (40 μg/kg) were dissolved in a 0.5 % lactic acid solution in distilled water; 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-adrenoreceptor agonist clonidine (10 and 400 μg/kg), and the 5-TH1A receptor antagonist WAY 100.635 were dissolved in distilled water. The selective α1A-adrenoreceptors antagonist (Wetzel et al., 1995) SNAP 5089 (1 mg/kg) was dissolved in 20 % beta-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 electrophysiological 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 2-6 MΩ. Neurons in the CA3
region of the hippocampus and lateral geniculate nucleus (LGN) were recorded with a 5-barrel micropipette (impedances: central barrel 2-5 MΩ, side barrels 20-30 MΩ). The central barrel, used for unitary recordings, and one sidebarrel, used for automatic current balancing, were filled with 2 M NaCl; the other barrels were filled with brexpiprazole (1.2 mM in distilled water and 0.5% lactic acid, pH=4.5), 5-HT creatinine sulfate (10 mM in 0.2 M NaCl, pH=4), NE (10 mM in 0.2 M NaCl, pH=4) or quisqualalic acid (1.5 mM 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 nA to-90 nA, respectively) and retained with a positive current.

**Recording of 5-HT neurons**

Putative 5-HT neurons were recorded by positioning single-barrel glass micropipettes at the following coordinates (in mm from lambda): anterior/posterior (AP) 1.0 to 1.2, mediolateral (ML) 0, dorsal/ventral (DV) 5.0 to 7.0. At these coordinates, only neurons with a bi- or triphasic extracellular waveform with a long-duration (0.8-1.2 ms) 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 mm from lambda): AP -1.0 to -1.2, ML 1.0 to 1.3, DV 5.0 to 7.0. NE neurons were identified using the following criteria: regular firing rate (1-3 Hz), a long duration (0.8-1.2 ms) of the rising phase of the action potential, and a brisk excitatory response followed by a short period of inhibition (~1 s) in reaction to a nociceptive 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 mm from lambda): AP 3.2 to 3.6, ML 0.6 to 1.0, DV 7.0 to 9.0. At these coordinates, neurons with a long-duration (3-5 ms) triphasic action potential with a marked negative deflection, an inflection or “notch” on the rising phase, 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 2 spikes within 80 ms; end of a burst was defined as an ISI>160 ms (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 pharmacological 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 lateral geniculate nucleus (LGN) neurons

LGN neurons were recorded by positioning multibarrel micropipettes at the following coordinates (in mm from lambda): AP 3.8-4.2, ML 4.0-4.2, 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 α1-adrenergic receptors (Rogawski and Aghajanian, 1980, 1982; Menkes et al., 1981). Since adrenoceptors of the 1B subtype are densely expressed in the dorsal LGN, whereas α1B-adrenoceptors are absent and there is minimal presence of α1B-adrenoceptors (Day et al., 1997), the LGN was chosen to assess the effect of brexpiprazole on α1B-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 ejections 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 mm from lambda): AP: 3.8-4.2, L: 4.0-4.2, D 3.5-4.5. Since most CA3 pyramidal neurons are not spontaneously active in chloral hydrate anesthetized rats, a small ejection current (-1 to +1 nA) was applied to the quisqualate barrel in order to activate them within their physiological firing range (10 to 15 Hz; Ranck 1973). The current and duration of 5-HT and NE ejection was kept constant before and after each i.v. injection of brexpiprazole. Neuronal responsiveness to the iontophoretic application 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 at RT50 (De Montigny et al., 1980). Neural responsiveness to 5-HT was assessed by determining the total number 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 recovery time (in seconds) from the end of a 50-second ejection of 5-HT (20 nA) that fully inhibited the neuron, to 50% recovery of baseline firing and was expressed as RT50 (Piñeyro et al., 1994). Partial or full agonism of brexpiprazole on 5-HT1A receptors was assessed by comparing the inhibitory effect of ejection 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 quisqualate ejection. In this paradigm, co-application of partial agonist reduces the inhibitory effect of 5-HT, whereas co-application of a full agonist does not change the inhibitory effect of 5-HT (Dong et al., 1998; Ghanbari 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 100.635 (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 mm from lambda): AP +1.0, L0.0, D: 7.8-8.2, in order to electrically stimulate 5-HT afferents while recording a CA3 pyramidal neuron using a multibarrel pipette (see above). A stimulator (S8800, Grass instruments, Quincey, MA) was used to deliver 200 square pulses (0.5 ms, 1 or 5 Hz) at 300 μA. Duration of inhibition per stimulation was plotted in a peristimulus time histogram with a 2 ms bin size. The inhibitory effect of 5-HT fiber stimulation on CA3 neurons was expressed as duration of silence (DOS, in ms), defined as the period from the first bin showing a 50% reduction in the number of events per bin from the prestimulus 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-HT\textsubscript{1A} receptors, an effect previously shown to be independent of 5-HT reuptake inhibition (Chaput et al., 1986). To determine the action of brexpiprazole on α\textsubscript{2}-adrenoceptors on 5-HT terminals, we determined whether brexpiprazole (500 μg/kg, i.v.) could prevent and, in a subsequent experiment, reverse the decreasing effect on DOS of a high dose of the α\textsubscript{2}-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 α\textsubscript{2}-adrenergic autoreceptors on NE terminals and so decreases NE tone on α\textsubscript{2}-adrenoceptors located on 5-HT terminals, resulting in an increased DOS. A subsequent high dose of clonidine activates α\textsubscript{2}-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-HT\textsubscript{1B} autoreceptors, the effect of 3 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-HT\textsubscript{1B} receptors and consequently, decreased 5-HT release. Therefore, a longer DOS following 1 Hz compared to 5 Hz stimulations is
indicative for functional terminal 5-HT\textsubscript{1B} autoreceptors (Chaput \textit{et al.}, 1986; Blier \textit{et al.}, 1989).

**Data analysis / Statistics**

Electrophysiological recordings made, and filtered from artifacts by wavemark analysis, using Spike2 software version 6.17 (Cambridge Electronic Design, Cambridge, United Kingdom). Quantification of firing activity was performed using Spike2, with the exception of firing and burst analysis of VTA DA neurons for which burstiDAtor (Oosterhof and Oosterhof, 2013) software was used. In experiments when no competitive exogenous ligand was present, linear regression analysis was used to determine ED\textsubscript{50} values, and to compare the slope and intercept when comparing the effect of aripiprazole and brexiprazole. In presence of a competitive exogenous ligand, non-linear curve fitting was used to obtain ED\textsubscript{50} values. Experiments with less than 3 observations within the same subject were analyzed with a paired t-test; experiments with more than 3 observations within the same subject were analyzed with repeated measurements analysis of variance followed by a Tukey \textit{post-hoc} test. All data were analyzed with Graphpad Prism (Version 5.01, Graphpad software, La Jolla, CA). Data is presented as mean ± S.E.M.; a p-value <0.05 was considered significant.
6. Results

Effect of brexpiprazole and aripiprazole on VTA DA neurons

Brexipiprazole 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, figure 1C) or bursting activity (F_{1,29}=1.61, n=10, p=0.21 figures 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, figures 1C) and bursting activity of VTA DA neurons (F_{1,18}=7.58, n=5, p=0.013, figures 1D). For an illustrative trace of the effect of brexpiprazole and aripiprazole see figures 1A and 1B, respectively.

Effect of brexpiprazole on D_{2} 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 approximately 65% of baseline firing. Sigmoidal curve fitting (n=9) yielded an ED_{50} value of 61 μg/kg for brexpiprazole on this effect (figure 2B; for an illustrative trace see figure 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 neurons (n=11), an effect not reversed by administration of the NE reuptake inhibitor desipramine (5 mg/kg) whereas the selective 5-HT_{1A} antagonist WAY 100.635 reversed this inhibition (n=3, for an illustrative trace see figure 3A). Similarly, an inhibitory effect of aripiprazole was observed on 5-HT neurons (n=15) that was reversed by the selective 5-HT_{1A} antagonist WAY 100.635 but not desipramine (n=3). For aripiprazole, the experiment was initially conducted by administering cumulative doses of 200 μg/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 μg/kg, aripiprazole was administered at 500 μg/kg (n=9) in a subsequent experiment; data of these experiment were pooled, as statistical analysis demonstrated that the dose-responsiveness of DRN neurons to aripiprazole at increments of 200 μg/kg
and 500 μg/kg were 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 (ED\(_{50}\) = 230 and 700 μg/kg, respectively, F\(_{1,78}=31.51, p<0.0001\), figure 3B).

**Effect of brexpiprazole on postsynaptic 5-HT\(_{1A}\) receptors**

In the hippocampus, systemic administration of brexpiprazole up to a dose of 1500 μg/kg did not change the number of spikes suppressed/nA following iontophoretic application of 5-HT on CA3 pyramidal neurons (F\(_{1,30}=2.72, p>0.05\); 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 figure 4A). When brexpiprazole and 5-HT were ejected concomitantly, the neuronal inhibition of CA pyramidal neurons did not differ from when 5-HT was ejected alone (p>0.05, n=12, figure 4D). This inhibitory effect of both agents was significantly dampened after systemic administration of the 5-HT\(_{1A}\) receptor antagonist WAY 100.635 (p<0.05 and p<0.01, respectively, figure 4B and 4C).

**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 administrations of brexpiprazole up to a dose of 1500 μg/kg (F\(_{1,32}=0.47, p>0.05\); data not shown).

**Effect of brexpiprazole on terminal 5-HT\(_{1B}\) autoreceptors**

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 μg/kg (figure 7B). For 5 Hz stimulations, the corresponding DOS at these doses were 27 ± 2, 38 ± 3, 48 ± 5 and 49 ± 4. 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 (slope: F\(_{1,36}=0.91, p>0.05\), intercept: F\(_{1,37}=13.96, p=0.0006\)).
Effect of brexpiprazole on 5-HT\textsubscript{2A} receptors in the LC

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

Effect of brexpiprazole on postsynaptic \(\alpha\textsubscript{1B}\)-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 (\(F_{2,5}=20.10, p=0.0034, p<0.05\) and \(p<0.001\) for these respective doses, figure 6B) with an ED\textsubscript{50} value estimated at 630 \(\mu\)g/kg. The excitatory effect of NE ejection was not changed by prior administration of the \(\alpha\textsubscript{1A}\)-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 illustration see figure 6A).

Effect of brexpiprazole on postsynaptic \(\alpha\textsubscript{2}\)-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/nA following iontophoretic application of NE (\(F_{1,28}=0.95, p>0.05\); data not shown).

Effect of brexpiprazole on the NET

In the hippocampus CA3 region, the RT\textsubscript{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 \(\alpha\textsubscript{2}\)-adrenoceptors on 5-HT terminals

Clonidine at a dose of 10 \(\mu\)g/kg significantly increased the DOS value following 1 Hz stimulation compared to baseline, an effect completely reversed by a subsequent injection of clonidine at a dose of 400 \(\mu\)g/kg (\(F_{3,5}=13.63, n=6, p<0.0001\), figure 7A). Following these doses of clonidine, the DOS increased with cumulative administrations
of brexpiprazole (500, 1000 and 1500 μg/kg, i.v.) in a dose-dependent fashion (Tukey post-hoc, 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 (F₃,₄=4.16, n=5, p=0.02, figure 7B). Tukey post-hoc testing revealed a significant effect of brexpiprazole on DOS at a dose of 1000 and 1500 μg/kg (p<0.01 and p<0.01, respectively). Clonidine administration (10 and 400 μg/kg) had no altering effect on the DOS when it was administered after brexpiprazole (p>0.05, figure 7B).
7. Discussion

**Brexpiprazole: effect on VTA DA neurons**

Brexpiprazole reversed the inhibitory action of the DA agonist apomorphine on neural firing of VTA DA neurons, thus demonstrating antagonistic action at D2 autoreceptors (figure 2). Interestingly, brexpiprazole by itself did not significantly change the firing rate or bursting activity of DA neurons (figure 1). In contrast, the classical D2 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 D2 autoreceptors (Pucak and Grace, 1994). Since brexpiprazole did not alter firing and bursting activity of VTA DA neurons, this result demonstrates that in vivo, it neither acts as a pure antagonist, nor as an agonist with high intrinsic activity on D2 autoreceptors. Aripiprazole, similar to brexpiprazole, was previously shown to reverse 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 (figure 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 D2 receptors, in line with their in vitro profiles (Maeda, Sugino, et al., 2014). Notably, the present study also demonstrated more potent in vivo agonism of brexpiprazole on 5-HT1A receptors than aripiprazole (discussed below). Since 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.

**Brexpiprazole: effect on the 5-HT system**

Brexpiprazole dose-dependently inhibited the firing rate of 5-HT neurons in the DRN (figure 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 (figure
Compared to aripiprazole, brexpiprazole was significantly more potent at activating 5-HT$_{1A}$ autoreceptors (figure 3B), a finding in line with the in vitro affinity for 5-HT$_{1A}$ receptors of these agents (Maeda, Sugino, et al., 2014). 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 μg/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 μg/kg. The reason for this difference remains to be established, although linear vs. 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 (figure 4A,C), an effect attributable to 5-HT$_{1A}$ activation. Indeed, the inhibitory effect of these agents was blocked after systemic administration of the 5-HT$_{1A}$ antagonist WAY 100.635 (figure 4B,C). Importantly, the inhibitory effect of 5-HT alone was unaltered when brexpiprazole was co-ejected (figure 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.

Brexiprazole administration dose-dependently increased the DOS following electrical stimulations of 5-HT afferents at 1 Hz (figure 7B), an effect that could theoretically be attributable to terminal 5-HT$_{1B}$ autoreceptors and/or $\alpha_2$-adrenergic heteroceptor antagonism (Chaput et al., 1986; Mongeau et al., 1993). However, brexpiprazole administration did not change the difference in DOS following 1 and 5 Hz stimulations, indicating that terminal 5-HT$_{1B}$ autoreceptors functionality was unaffected by brexpiprazole. In contrast, brexpiprazole acted as a potent $\alpha_2$-adrenergic heteroceptor antagonist, as shown in two complementary experiments where brexpiprazole reversed
(figure 7A) and prevented (figure 7B) the typical decrease in DOS caused by a high dose of the $\alpha_2$-adrenoceptor agonist clonidine (400 $\mu$g/kg, i.v.). Such effects have previously been observed following acute administration of the antidepressants mianserin and mirtazapine (Mongeau et al., 1993; Haddjeri et al., 1996).

**Brexpiprazole: effect on the NE system.**

In the LC, NE neurons are innervated by inhibitory GABA neurons that express excitatory 5-HT$_{2A}$ receptors; activation of 5-HT$_{2A}$ receptors enhances GABA neurotransmission and inhibits NE neurons (Szabo and Blier, 2001). Indeed, systemic administration of the preferential 5-HT$_{2A}$ receptor agonist DOI strongly inhibited NE neurons. Since this effect was potently reversed by brexpiprazole, antagonistic action of this agent on 5-HT$_{2A}$ receptors was clearly demonstrated (figure 5). In the present study, the ED$_{50}$ value of brexpiprazole for 5-HT$_{2A}$ receptors antagonism was approximately 2-fold higher than for D$_2$ receptor antagonism (110 vs. 61 $\mu$g/kg, respectively), which is qualitatively in line with its *in vitro* profile (Maeda, Sugino, et al., 2014). Notably, caution should be taken when comparing *in vitro* and *in vivo* data of agents in their effectiveness to reverse the action of receptor agonists, since ED$_{50}$ values are relative to the affinity, intrinsic activity, and dose of the used agonist. Additionally, the multiple receptor activity of brexpiprazole could affect more than one neuronal substrate *in vivo*. To illustrate this point, the *in vitro* affinity of asenapine is one order of magnitude greater for 5-HT$_{2A}$ than D$_2$ receptors (Shahid et al., 2009), whereas the *in vivo* ED$_{50}$ value for D$_2$ receptors type was found to be approximately two-fold higher than for 5-HT$_{2A}$ receptors (Ghanbari et al., 2009).

In the hippocampus CA3 region, brexpiprazole did not modify the inhibitory response to iontophoretic application of NE or the RT$_{50}$ index, indicating no action on postsynaptic $\alpha_2$-adrenoceptors and the NET, respectively (De Montigny et al., 1980; Curet and de Montigny, 1988). In the LGN, neurons are known to almost exclusively express $\alpha_1$-adrenergic receptors of the 1B subtype (Day et al., 1997). In this brain region, the antagonistic effect of brexpiprazole on these receptors was assessed by quantifying neuronal excitation following iontophoretically applied NE, a response known to be mediated by $\alpha_1$-adrenoceptors (Rogawski and Aghajanian, 1980, 1982; Menkes et al.,...
1981). Neuronal excitation decreased with brexpiprazole administration, strongly suggesting antagonistic action at $\alpha_1$-adrenergic receptors (figure 6B). Since there is no expression of $\alpha_{1B}$-adrenoreceptors yet minimal expression of $\alpha_{1A}$-adrenoceptors, (Day et al., 1997), the excitatory effect of NE after administration of the selective $\alpha_{1A}$-adrenoreceptor antagonist SNAP 5089 was assessed (Wetzel et al., 1995). The excitatory effect of iontophoretic application of NE on LGN neurons was not altered by SNAP 5089 administration, whereas consecutive administrations of brexpiprazole largely blocked this excitatory effect (figure 6A). Taken together, these result suggests antagonistic properties of brexpiprazole predominantly at $\alpha_{1B}$-adrenoceptors, consistent with its 20-fold higher affinity for this receptor subtype over $\alpha_{1A}$- and $\alpha_{1D}$-adrenoceptors (Maeda, Sugino, et al., 2014).

**Conclusion**

The present results show acute *in vivo* action of brexpiprazole at all three monoamine (5-HT, NE and DA) systems. Similar to aripiprazole, brexpiprazole acted as a partial D$_2$ receptor agonist *in vivo*, but is relatively less efficacious at this receptor type. Clinically, D$_2$ receptor partial agonism is thought to buffer fluctuations in DA transmission (Burris, 2002; Shapiro et al., 2003), in line with the behavioural effects of brexpiprazole in animal models for schizophrenia (Maeda, Lerdrup, et al., 2014). Furthermore, the potent *in vivo* agonistic action on 5-HT$_{1A}$ receptors of brexpiprazole could be a relevant pharmacological feature in treatment of both mood disorders and schizophrenia (Blier and Ward, 2003; Newman-Tancredi, 2010). Acute brexpiprazole reduced inhibition on two important interaction nodes between the 5-HT and NE system; first it blocked 5-HT$_{2A}$ 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 $\alpha_2$-adrenoceptors on 5-HT 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$_{2A}$ receptor antagonism 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 clinically efficaciousness of brexpiprazole as adjunct to
antidepressants in major depressive disorder (Thase et al., 2014). In addition, combined but not separate administration of brexipiprazole and NE or 5-HT reuptake inhibitors had an antidepressant-like effect in rodents (Hirose et al., 2014). Following this in vivo pharmacological characterization and since brexipiprazole will be administered on long-term basis in the clinic, it will be crucial to investigate the effect of sustained brexipiprazole administration on therapeutically relevant monoamine targets.
8. Acknowledgements

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Conducted experiments: C.A. Oosterhof.

Performed data analysis: C.A. Oosterhof.

Wrote or contributed to the writing of the manuscript: C.A. Oosterhof, M. El Mansari, P. Blier.
10. References


11. Footnotes.

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12. Legends to figures.

Figure 1: effect of systemic brexpiprazole and aripiprazole administration on VTA DA neurons. A, B: illustrative trace of DA neurons and response to intravenous administration of brexpiprazole (black arrows, figure A) and aripiprazole (grey arrows, figure B). C, 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. *Significant effect of brexpiprazole in comparison to saline administration, **slope: p<0.01, ##intercept: p<0.01.

Figure 2: effect of systemic brexpiprazole administration on VTA DA neurons inhibited by the dopamine agonist apomorphine. A: illustrative trace of a DA neurons 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.

Figure 3: effect of systemic brexpiprazole and aripiprazole administration on 5-HT neurons in the DRN. A: illustrative trace of a 5-HT neuron and response to intravenous administration brexpiprazole. B: brexpiprazole (n=11) is a more potent 5-HT$_{1A}$ agonist than aripiprazole (n=15). Data were analyzed using linear regression and are presented as mean ± S.E.M.

Figure 4: effect of iontophoretically applied brexpiprazole, 5-HT, and concomitant ejection of 5-HT and brexpiprazole on pyramidal neurons in the hippocampus CA3 region. A: illustrative trace of discharge activity of a pyramidal neuron in the CA3 region of hippocampus, and effects of iontophoretically applied agents before and after systemic WAY 100.635 (WAY) administration. B, C: the inhibitory response to iontophoretic application of brexpiprazole and 5-HT is significantly reduced after WAY administration. D: There was no different inhibitory effect of co-ejection of brexpiprazole and 5-HT.
compared to 5-HT ejection alone. The number of neurons (n) and animals (a) is presented in histograms; data were analyzed with a paired t-test and are presented as mean ± S.E.M.

*Significant effect of WAY 100.635 administration on the inhibitory effect of brexpiprazole and 5-HT; *p<0.05, **P<0.01.

Figure 5: effect of systemic brexpiprazole on LC NE neurons inhibited by the preferential 5-HT2A agonist DOI. A: illustrative trace of an NE neuron inhibited by intravenous administration of DOI and reversal of inhibition by brexpiprazole. Between 720-740 seconds the electrical signal of the neuron decreased below the level of the differential amplitude discriminator. Following this decrease, the electrode was quickly lowered by ~20 micrometer and the signal was restored to its prior amplitude. Wavemark analysis confirmed that the same neuron was recorded before and after this period. B: graphic presentation of the reversing effect of brexpiprazole on neurons inhibited by DOI (n=10). The ED50 value was obtained with simple non-linear regression; data are presented as mean ± S.E.M.

Figure 6: effect of brexpiprazole on the excitatory effect of iontophoretically applied NE on LGN neurons. A: illustrative trace of the electrical activity of an LGN neuron, its excitation by iontophoretically applied NE, ineffectiveness of the selective α1A-adrenergic receptor antagonist SNAP 5089 to alter this excitation, blockade of this excitation by systemic brexpiprazole administration, and brisk excitatory response to light flashes, confirming proper recording electrode positioning. B: effect of brexpiprazole on the excitatory response of LGN neurons to iontophoretic application of NE. The number of neurons tested is presented in histograms; data were analyzed with repeated measures ANOVA and Tukey post-hoc, and are presented as mean ± S.E.M.

*Significant effect of brexpiprazole administration; *p<0.05, ***P<0.001.

N.B. Data from the neuron recorded in (A) were not included in (B) due to the injection of SNAP 5089 prior to brexpiprazole administration.

Figure 7: effect of brexpiprazole on α2-heteroceptors located on 5-HT terminals. A: schematic presentation of the effect of three cumulative doses of brexpiprazole (500
μg/kg, i.v.) after clonidine (10 and 400 μg/kg, i.v.) on DOS (n=6). B: effect of three cumulative doses of brexpiprazole (3 x 500 μg/kg, i.v.) on DOS alone, and absence of effect of clonidine on DOS after brexpiprazole administration (n=5). Brex; brexpiprazole, Cl; clonidine, numbers after abbreviations indicate doses in μg/kg, numbers in brackets indicate first, second or third administration of brexpiprazole. Data were analyzed with repeated measures ANOVA followed by a Tukey post-hoc test, and are presented as mean + S.E.M.

*Significant effect of brexpiprazole administration on DOS relative to clonidine 400 μg/kg (A) and baseline values (B), respectively. #significant effect of clonidine administration on DOS compared to baseline. *p<0.05, **P<0.01, ***P<0.01; ##P<0.01).
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1B

Bursts

Vehicle 200 µg/kg 400 µg/kg aripiprazole

Spikes/10s

VTA DA neuron

Time (s)
Figure 2A: Vehicle, Apomorphine 40µg/kg, Brexpiprazole 25 µg/kg. VTA DA neuron.
3A

- **Vehicle**
- **Brexiprazole 100 µg/kg**
- **WAY 100.635 100 µg/kg**
- **Desipramine 5 mg/kg**

**Time (s)**

**Spikes/10s**

**DRN 5-HT neuron**

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WAY 100.635 100 µg/kg, i.v.
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DOI 10.1124/jpet.114.218578

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Dose of brexipiprazole (μg/kg)
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![Graph showing DOS (ms) with bars for different conditions.](image-url)

The graph shows a comparison of DOS (ms) for different conditions, with significance levels indicated as follows:
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- **###** for p < 0.001
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**DOS (ms)**

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