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Extrastriatal dopaminergic circuits of the basal ganglia

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INTRODUCTION

The basal ganglia consist of the striatum, the external and internal segment of the globus pallidus (GPe and GPi, respectively), the subthalamic nucleus (STN), and the substantia nigra pars compacta and reticulata (SNc and SNr, respectively). Dopamine has long been identified as an important modulator of basal ganglia function in the striatum, and disturbances of striatal dopaminergic transmission have been implicated in diseases such as Parkinson’s disease (PD), addiction and attention deficit hyperactivity disorder. However, recent evidence suggests that dopamine may also modulate basal ganglia function at sites outside of the striatum, and that changes in dopaminergic transmission at these sites may contribute to the symptoms of PD and other neuropsychiatric disorders. This review summarizes the current knowledge of the anatomy, functional effects and behavioral consequences of the dopaminergic innervation to the GPe, GPl, STN, and SNr. Further insights into the dopaminergic modulation of basal ganglia function at extrastriatal sites may provide us with opportunities to develop new and more specific strategies for treating disorders of basal ganglia dysfunction.

Keywords: subthalamic nucleus, globus pallidus, substantia nigra, Parkinson’s disease, basal ganglia, dopamine, GABA, glutamate

CIRCUIT ANATOMY OF THE BASAL GANGLIA

The basal ganglia are components of larger functionally and anatomically segregated circuits that also involve the cerebral cortex and thalamus (Alexander et al., 1986, 1990; Hoovers and Strick, 1993; Middleton and Strick, 1997, 2002; Kelly and Strick, 2004; Mallet et al., 2007; Wichmann and Delong, 2007). The “motor” circuit originates in the frontal cortical motor areas and involves motor portions of the striatum, GPe, STN, GPl, SNr, and thalamus, returning to the frontal cortex. “Associative” and “limbic” circuits originate from the prefrontal associative and limbic cortices and involve related areas in the basal ganglia and thalamus separate from those occupied by the motor circuit. While the motor circuit is thought to be involved in the control of movement, the associative circuit may play a role in the control of executive functions, and the limbic circuit in the control of emotions and motivation. Dysfunction in elements of these circuits may contribute to diseases ranging from classical movement disorders, such as Parkinson’s disease (PD), to neuropsychiatric conditions, such as Tourette syndrome or addiction.

The anatomy of individual connections within these circuits has been described in considerable detail. Within the basal ganglia, the striatum and STN serve as input stations, while GPl and SNr serve as output stations. Glutamatergic efferents from cortex and thalamus project to the striatum and STN in a topographically organized manner (Alexander et al., 1986, 1990; Middleton and Strick, 2002; Kelly and Strick, 2004; Mallet et al., 2007; Wichmann and Delong, 2007). The input and output nuclei of the basal ganglia are connected through two main pathways, i.e., the monosynaptic GABAergic “direct” pathway and polysynaptic “indirect” pathway. The indirect pathway involves GABAergic projections from the striatum to GPe and from GPe to the STN, as well as excitatory glutamatergic projections from the STN to GPe, GPl, and SNr.

At the most basic level of analysis, the polarities of the connections within the direct and indirect pathways oppose one another. Activation of the striatal neurons of the direct pathway have predominately net inhibitory effects on GPl/SNr activity, while activation of the striatal neurons of the indirect pathway have net excitatory effects on them. This scheme is too simplistic, however, as the interactions between and within the two pathways may shape firing patterns independent of firing rates (e.g., oscillatory and burst patterns of discharge, in the GPl/SNr; Galvan and Wichmann, 2008).

The GPl and SNr send topographically organized GABAergic projections to the thalamus and brainstem. Motor circuit output from the GPl and SNr reaches the anterior portion of the ventrolateral thalamic nucleus (VLa), which then project back...
to motor areas of the frontal cortex. In contrast, associative circuit output from the SNr and Gpi, reaches the thalamic ventral anterior (VA) nucleus, which sends efferents to the dorsolateral prefrontal cortex and the lateral orbitofrontal cortices (Hoover and Strick, 1993; Haber et al., 1995; Kaneda et al., 2002; Romanelli et al., 2005). Collaterals of the Gpi/SNr projection to the ventral thalamus reach the intralaminar thalamic centromedian and parafascicular nuclei (CM/PF), as well as brain stem targets such as the pedunculopontine nucleus, and the reticular formation (Smith et al., 2009).

STRATIAL ACTIONS OF DOPAMINE

It has been known for many decades that the neurotransmitter dopamine is present in high concentrations in the basal ganglia. The dopamine supply to these structures originates in the midbrain dopaminergic nuclei, the SNC and ventral tegmental area. The striatum is the most prominent release site for dopamine in the basal ganglia, influencing the overall balance of activity along the direct and indirect pathways via different types of dopamine receptors (Gerfen et al., 1990). D1-like receptors (D1LR, including D1- and D5-receptors; Clark and White, 1987; Neve, 1997) are found on striatal neurons that give rise to the direct pathway, while D2-like receptors (D2LRS, including D2-, D3-, and D4-receptors; Neve, 1997) are found on striatal neurons that give rise to the indirect pathway (see, for instance, recent studies in transgenic mice; Heintz, 2001; Day et al., 2006; Wang et al., 2006). Activation of D1LRs on direct pathway neurons is thought to facilitate corticostriatal transmission, while activation of D2LRs on indirect pathway neurons appears to reduce corticostriatal transmission (Gerfen et al., 1990; Gerfen, 1995). According to traditional models of the basal ganglia, the dopamine-mediated increase in activity of the inhibitory direct pathway, in conjunction with the dopamine-mediated reduction of activity in the net excitatory indirect pathway leads to an overall reduction of activity of Gpi/SNr neurons, acting to disinhibit thalamocortical projection neurons. In addition to the regulation of transmission along direct and indirect pathways, striatally released dopamine is also implicated in the modulation of learning and neuronal plasticity through processes such as long-term depression (LTD) or potentiation (LTP), acting at glutamatergic synapses (Aosaki et al., 1994; Cragg, 2003; Picconi et al., 2003; Wang et al., 2006; Calabresi et al., 2007; Kreitzer and Malenka, 2007; Schultz, 2007; Flajolet et al., 2008; Kreitzer and Malenka, 2008; Pawlak and Kerr, 2008).

The duration of action and diffusion of dopamine are to some extent regulated by dopamine transporter- (DAT-) mediated uptake (Blakely and Bauman, 2000; Cenci and Lundblad, 2006; Rice and Cragg, 2008). In rodent studies, it has been shown that DAT concentrations and dopamine clearance rates differ among striatal territories, with a dorso-ventral gradient (Missale et al., 1985; Kuhr et al., 1986; Stamford et al., 1988; Letchworth et al., 2001). Given the topographical organization of the striatum, such differences may affect the physiologic role and significance of dopamine in different behavioral domains. For instance, physiological data indicate that the time course of DA signaling may determine the pattern of dopamine-glutamate interaction in different areas of the striatum (Calabresi et al., 2000; Wickens et al., 2003).

EXTERNAL ACTIONS OF DOPAMINE

EXTERNAL PALILLARY SEGMENT

Anatomical studies

The GPe is a component of the indirect pathway, receiving GABAergic inputs from the striatum (Chang et al., 1981; Filion and Tremblay, 1991; Sidibe and Smith, 1996; Raz et al., 2000), and sending GABAergic projections to STN, Gpi, and SNr (Morizumi et al., 1992; Parent and Hazrati, 1995a,b). Several studies have shown that the primate globus pallidus (GP) receives dopaminergic inputs that are differentially distributed in GPe and Gpi, with dopamine fibers arborizing profusely in the GPe and more sparsely in dorsal portion of the GPe (Parent and Smith, 1987; Lavoie et al., 1989; Parent et al., 1989; Hedreen, 1999). Some of these fibers are passing through the pallidum en route to the striatum. However, retrograde and anterograde labeling studies in rats and monkeys have shown that at least some of these fibers arise as a nigropallidal projection that is separate from the nigrostriatal projection (Fallon and Moore, 1978; Lindvall and Bjorklund, 1979; Smith et al., 1989; Gauthier et al., 1999; Jan et al., 2000; Smith and Kieval, 2000; Anaya-Martinez et al., 2006). Low levels of dopamine (Pifl et al., 1990) as well as DAT immunoreactivity and DAT ligand binding have also been detected in postmortem studies on human GPe tissue (Ciliax et al., 1999; Porritt et al., 2005) and rodent GP, the rodent homologue of the primate GPe (Ciliax et al., 1995; Coulter et al., 1995) indicating the presence of terminals of a dopaminergic projection in the GPe.

Dopamine receptors are found at pre- and postsynaptic locations in GPe (Table 1). Most of the presynaptic dopamine receptors are thought to be D2LRS, and are located on terminals of the GABAergic striatopallidal projection (Parent and Smith, 1987; Gerfen et al., 1990; Deng et al., 2006). Using electron microscopy we recently confirmed the presence of presynaptic D2-receptors in the monkey GPe on putatively GABAergic axons and terminals, with sparse labeling of putatively glutamatergic terminals (unpublished observation). A previous rat study identified D4-receptors primarily on axons and on a few putatively glutamatergic terminals in GP (Rivera et al., 2003).

There is also evidence for postsynaptic expression of D2LRs in GPe. For example, D2- and (less) D3-receptor mRNA has been found in the human GPe (Murray et al., 1994). However, another study did not confirm D3-receptor mRNA expression in monkeys (Quik et al., 2000). In rats, D2-receptor mRNA was found, particularly in pallidal cells projecting to the striatum (Marshall et al., 2001; Hoover and Marshall, 2004). Low levels of D2-receptor protein labeling have been detected in human GPe (Levey et al., 1993) and in postsynaptic structures in the rat (Yung et al., 1995). Scattered cell bodies in the rat GP showed immunoreactivity for D2-, D3-, and D4-receptor (Khan et al., 1998). In the monkey, both D3- (Quik et al., 2000) and D4-receptors (Mrzljak et al., 1996) have been found. The latter are associated with the parvalbumin-positive GABAergic neurons which project predominantly to the basal ganglia output nuclei (Mrzljak et al., 1996).

In addition to these D2LRS, lower levels of D1LRs have been detected, in axons and terminal boutons forming symmetric, putatively GABAergic synapses in the rodent GP (Levey et al., 1993; Yung et al., 1995). D5-receptors were identified in the rodent GP and monkey GPe (Ciliax et al., 2000; Khan et al., 2000).
### Table 1 | Dopamine receptor localization in the extrastriatal basal ganglia.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Synaptic location</th>
<th>D1LRs</th>
<th>D2LRs</th>
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<td>D1</td>
<td>D5</td>
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<td>GPe</td>
<td>Pre</td>
<td>Axons, GABA terminals <strong>R</strong> (Levey et al., 1993; Yung et al., 1995)</td>
<td>GABA terminals <strong>R</strong> (Levey et al., 1993), <strong>M</strong> (unpublished observations)</td>
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<td></td>
<td>Post</td>
<td><strong>R</strong> (Levey et al., 1993), <strong>M</strong> (unpublished observations)</td>
<td><strong>R</strong> (Rivera et al., 2003)</td>
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<td>STN</td>
<td>Pre</td>
<td>Terminals <strong>M</strong> (Rommelfanger et al., 2010)</td>
<td>Terminals <strong>M</strong> (Rommelfanger et al., 2010)</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>Dendrites <strong>R</strong> (Baufreton et al., 2003), <strong>M</strong> (Rommelfanger et al., 2010)</td>
<td><strong>R</strong> (Rivera et al., 2003)</td>
</tr>
<tr>
<td>GPI</td>
<td>Pre</td>
<td>Axons <strong>R</strong> (Yung et al., 1995), <strong>M</strong> (Kliem et al., 2010)</td>
<td>Axons <strong>M</strong> (Kliem et al., 2010)</td>
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<td></td>
<td>Post</td>
<td>Dendrites <strong>M</strong> (Kliem et al., 2010)</td>
<td><strong>M</strong> (Rivera et al., 2003)</td>
</tr>
<tr>
<td>SNr</td>
<td>Pre</td>
<td>GABA terminals <strong>R</strong> (Levey et al., 1993; Yung et al., 1995; Caille et al., 1996)</td>
<td>GABA and glutamate terminals <strong>M</strong> (unpublished observations)</td>
</tr>
<tr>
<td></td>
<td>Post</td>
<td>Dendrites <strong>M</strong> (Kliem et al., 2010), <strong>R</strong> (Khan et al., 2000)</td>
<td><strong>R</strong> (Rivera et al., 2003)</td>
</tr>
</tbody>
</table>

Only studies verifying the presence of receptor protein are included in this table.

H, human; M, monkey; R, rodent.
Functional studies
Substantia nigra pars compacta lesions in rodents and monkeys reduce dopamine levels in GPes (Parent et al., 1990; Jan et al., 2000; Fuchs and Hauber, 2004). Furthermore, in vivo microdialysis studies in rats have shown that dopamine is released in the GP, that local administration of high-potassium solutions increases dopamine concentrations in pallidal dialysates, and that the release is inhibited by reverse dialysis of the sodium channel blocker tetrodotoxin, or by the use of low-calcium-medium, supporting the notion that dopamine is released in a spike-dependent fashion at this site (Dewar et al., 1987; Pil et al., 1990; Hauber and Fuchs, 2000).

Given the predominance of D2LRs in GPes, it is likely that most actions of dopamine in GPes are mediated via D2LRs. Activation of pallidal D2LRs has been shown to increase the activity of GPe neurons (see Table 2). For instance, activation of D2LRs in the rat GP increases the expression of the immediate early gene c-fos (Billings and Marshall, 2003), and infusions of the non-specific dopamine receptor agonist apomorphine into the rat GP increases pallidal neuron activity (Napier et al., 1991). Our recent studies in primates have also demonstrated that the neuronal activity in GPes was increased after intra-GPe infusions of the D2LR agonist quinpirole (Hadipour Niktarash et al., 2008), and that infusions of the D2LR antagonist sulpiride lowered pallidal firing rates, suggesting that the pallidal D2LRs are occupied by endogenous dopamine under normal conditions (unpublished observations).

While some of the pallidal effects of D2LR ligands may be mediated by postsynaptic D4-receptors (Shin et al., 2003), most of them are likely due to presynaptic modulation of GABAergic transmission. GABA release in GPes originates from terminals of the “indirect” striatopallidal pathway, and from local axon collaterals of pallidal neurons (Parent et al., 1999, 2000; Kita et al., 2004). Given the high activity levels of pallidal neurons (DeLong, 1971; Anderson and Horak, 1985; Miller and DeLong, 1987; Tremblay et al., 1989; Matsumura et al., 1995; Nambu et al., 2000; Raz et al., 2001; Kita et al., 2004; Starr et al., 2005), it is likely that most of the pallidal GABA stems from local axon collaterals. To what extent collateral interactions influence pallidal activities remains unclear. Early studies in anesthetized rats showed that iontophoresis of dopamine or of amphetamine, a dopamine releasing agent, reduces GABAergic transmission in the pallidum (Bergstrom and Walters, 1984). Microdialysis studies showed that activation of D2LRs decreased GABA release in the rat GP while activation of D1LRs increased GABA release (Floran et al., 1990, 1997). Subsequent patch clamp recordings of GP neurons in rat brain slice demonstrated that activation of presynaptic D2LRs decreases GABA-A receptor-mediated currents in the pallidum (Cooper and Stanford, 2001).

Dopamine receptor activation may also modulate the glutamatergic inputs to the GPes from the STN (Kita and Kitai, 1987; Robledo and Feger, 1990; Smith et al., 1990; Hazrati and Parent, 1992; Shink et al., 1996; Nambu et al., 2000) or CM/PF (Mouroux et al., 1997; Yasukawa et al., 2004). In vitro patch clamp studies in rodent brain slices have suggested that activation of presynaptic D1LRs facilitates glutamate release (Hernandez et al., 2007) while activation of D2LRs reduces it (Hernandez et al., 2006). These effects are not mutually exclusive, indicating that the involved receptors may be located on different axon terminals.

Studies of behavioral effects
In general, activation of D1LRs or D2LRs in the rodent GP appears to facilitate movement. In support of this notion, local intra-pallidal infusions of D1LR or D2LR antagonists were found to induce akinesia in rats, likely by blocking the effects of endogenous dopamine on these receptors (Hauber and Lutz, 1999). Similarly, intra-pallidal infusion of D1LR agonists (Sanudo-Pena and Walker, 1998) increased general movement. Other studies have demonstrated that infusion of D1LR agonists, D2LR agonists (Koshikawa et al., 1990), or amphetamine (Costall et al., 1972a,b) induces stereotypic jaw movements. The behavioral effects of dopamine receptor activation in the GPes have not been examined in other species.

SUBTHALAMIC NUCLEUS
Anatomical studies
The STN consists of glutamatergic neurons that send most of their projections to GPes, GPi, and SNr (Smith and Parent, 1988). The activity of STN cells is strongly regulated by its afferents, including inhibitory GABAergic inputs from the GPes and glutamatergic inputs from the cerebral cortex (Mink, 1996; Nambu et al., 1996, 2002; Takada et al., 2001). Smaller projections from the intralaminar nuclei of the thalamus to the STN have also been described (Sugimoto et al., 1983; Lanciego et al., 2004).

Anatomical studies have demonstrated that the STN receives sparse collaterals from the nigrostriatal pathway which pass the nucleus at its dorsal surface (Lavoie et al., 1989; Hedreen, 1999; Augood et al., 2000; Francois et al., 2000). These inputs form symmetric synapses on dendrites of STN neurons in rats (Cragg et al., 2004) and monkeys (Smith and Kieval, 2000). In postmortem human brains, terminal-like tyrosine hydroxylase-positive elements were identified along the STN’s dorsal surface (Cossette et al., 1999). Anatomical studies using retrograde (Rinvik et al., 1979; Campbell et al., 1985; Francois et al., 2000) or anterograde tracers (Hassani et al., 1997; Gauthier et al., 1999; Francois et al., 2000) in rats and monkeys support the existence of an SNc–STN projection. Others have detected DAT binding in the rodent STN (Coulter et al., 1995) and found that DAT blockade in rodent slices of STN increases dopamine release as measured by voltammetry (Cragg et al., 2004). We have also noted low levels of DAT immunoreactivity in the monkey STN (unpublished observations) suggesting that dopamine terminals may be found in the STN.

Dopamine receptors exist in the STN (Smith and Kieval, 2000; Smith and Villalba, 2008), but their distribution and relative expression level need further investigation (Table 1). Receptor binding studies have demonstrated D1LRs in the rat and human STN (Boyon et al., 1986; Dawson et al., 1986, 1988; Mansour et al., 1992; Parry et al., 1994; Augood et al., 2000). Similarly, binding studies using ligands for D2LRs (Bouthenet et al., 1987; Johnson et al., 1994), or ligands preferring D1-, D2-, D3-, or D4-receptors (Flores et al., 1999) have detected binding targets in the rat STN. Using electron microscopy, we have recently identified presynaptic D1- and D2-receptors in the monkey STN (Rommelfanger et al., 2010).

The available data on dopamine receptor mRNA is contradictory, but suggest that a portion of the dopamine receptors in the STN are postsynaptically expressed. Several authors have described the presence of the mRNA for D1-, D2-, and D3-receptors (Flores et al.,
and for D5-receptors in the rat STN (Svenningsson and Le Moine, 2002; Baufreton et al., 2003). Other studies have confirmed the expression of modest amounts of mRNA for D2-receptors, but not of D1-receptors (Mansour et al., 1992; Hurd et al., 2001) or D3-receptors (Quik et al., 2000). Neither D1- nor D2-receptor mRNA expression was found in the human STN (Augood et al., 2000). Postsynaptic D5-receptor protein expression has been identified at the light and electron microscope level in rats and monkeys (Ciliax et al., 2000; Baufreton et al., 2003; Rommelfanger et al., 2010).

### Table 2 | Functional effects of dopamine receptor agonists.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Effects of dopamine or non-specific D1LR/ D2LR agonists</th>
<th>D1LR agonist effects</th>
<th>D2LR agonist effects</th>
</tr>
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<tbody>
<tr>
<td>GPe</td>
<td>Increases firing rate (Napier et al., 1991)</td>
<td>Increases glutamate release (Hernandez et al., 2007)</td>
<td>Increases firing rate (Hadjipour Niktarash et al., 2008; unpublished observations)</td>
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<td></td>
<td>Decreases GABA transmission (Bergstrom and Walters, 1984)</td>
<td>Increases GABA release (Florian et al., 1990)</td>
<td>Increases c-fos (Billings and Marshall, 2003)</td>
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<td></td>
<td>Increases GABA release (Florian et al., 1990)</td>
<td></td>
<td>Decreases GABA release (Florian et al., 1997)</td>
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<td>STN</td>
<td>Increases firing rate (Ni et al., 2001; Zhu et al., 2002; Cragg et al., 2004)</td>
<td>Increases firing rate (Mintz et al., 1988; Ni et al., 2001; Rommelfanger et al., 2010)</td>
<td>Increases firing rate (Rommelfanger et al., 2010)</td>
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<td></td>
<td>Decreases GABA transmission (Shen and Johnson, 2000; Cragg et al., 2004; Baufreton and Bevan, 2008)</td>
<td>Increases bursting (D5) (Baufreton et al., 2003)</td>
<td>Decreases GABA-A currents (Shen and Johnson, 2000; Cragg et al., 2004; Baufreton and Bevan, 2008)</td>
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<td>Increases oscillations (Shen and Johnson, 2000; Cragg et al., 2004)</td>
<td>Decreases firing rate (Hassani and Feger, 1999)</td>
<td>Decreases firing rate (Hassani and Feger, 1999)</td>
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<td>Decreases bursting (Baufreton and Bevan, 2008)</td>
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<td>Decreases glutamate transmission (Shen and Johnson, 2000)</td>
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<td></td>
<td>Decreases firing rate (Campbell et al., 1985; Hassani and Feger, 1999)</td>
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<td>GPi</td>
<td>Increases GABA release (Florian et al., 1990)</td>
<td>Decreases firing rate (Kliem et al., 2007a)</td>
<td>Decreases firing rate (Hadjipour Niktarash et al., 2008; unpublished observations)</td>
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<td>SNr</td>
<td>Decreases multiunit activity (Timmerman and Abercrombie, 1996)</td>
<td>Decreases firing rate (Timmerman and Abercrombie, 1996; Kliem et al., 2007a)</td>
<td>Decreases firing rate (unpublished observations)</td>
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<td></td>
<td>Increases GABA release (Florian et al., 1990)</td>
<td>Increases GABA release (Flere et al., 1996; Kliem et al., 2007a)</td>
<td>Inhibits GABA transmission (Martin and Waszczak, 1996)</td>
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<td>Increases oscillations (Kliem et al., 2007a)</td>
<td>Decreases GABA-A release (Matuszewich and Yamamoto, 1999; D4) (Acosta-Garcia et al., 2009)</td>
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<td>Increases bursting (Kliem et al., 2007a)</td>
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<td>Increased firing rate (Waszczak, 1990; Martin and Waszczak, 1994)</td>
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<td>Decreases GABA-A transmission (Miyazaki and Lacey, 1998; Radnikow and Misgeld, 1998)</td>
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<td>Increases glutamate release (Rosailes et al., 1997)</td>
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<td>Increases glutamate transmission (Ibanez-Sandoval et al., 2006)</td>
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Functional studies

Early studies of dopamine receptor activation in the STN suggested that dopamine receptor activation in the STN may act to decrease STN neuronal activity. Campbell et al. (1985) showed that iontophoretic application of dopamine or apomorphine in vivo decreased the activity of most STN neurons, while the non-specific dopamine receptor antagonist haloperidol increased neuronal firing. Other in vivo studies showed that microinjections of apomorphine or agonists acting at D1LRs or D2LRs into the STN reduced STN firing (Hassani and Feger, 1999). In vitro brain slice recording studies showed that dopamine reduces glutamatergic currents in the STN (Shen and Johnson, 2000).

However, more recent studies have supported the view that dopamine facilitates rather than inhibits neuronal firing in the STN (Table 2), via actions on D1LRs and D2LRs. Thus, activation of postsynaptic D1LRs were shown to increase STN activity (Baufreton et al., 2005a). This was specifically demonstrated for postsynaptic D5-receptors whose activation appears to potentiate burst firing in a subgroup of STN neurons (Baufreton et al., 2003).

There is also strong evidence for D2LR-mediated facilitation of STN activity. These may involve postsynaptic effects, as demonstrated by Zhu et al. (2002), but also prominent activation of presynaptic D2LRs. For example, activation of D2LRs in the STN was shown to reduce GABA-A receptor-mediated currents in STN neurons by reducing GABA release (Shen and Johnson, 2000; Floran et al., 2004). Studies by Cragg et al. (2004) showed that dopamine release occurs in the STN, and that dopamine depolarizes neurons, increases spontaneous spike generation, and reduces the magnitude and frequency of evoked GABA-A receptor-mediated inhibitory postsynaptic potentials in the STN. More recent in vitro brain slice recording studies confirmed that D2LR activation increases STN activity via a reduction of GABA release, and that this may result not only in firing rate changes, but also in a reduction of rebound bursting activities in this nucleus (Baufreton and Bevan, 2008; Johnson, 2008). Baufreton et al. (2005b) have proposed that the combined actions of dopamine on D1LRs and D2LRs on STN cells leads to increased firing and reduced bursting in most STN neurons (see also section on the effects of dopamine depletion below).

Facilitatory effects of dopamine receptor activation have also been demonstrated in several in vivo studies. For example, intra-subthalamic infusions of dopamine or of the D1LR agonist SKF38393 activated STN neurons in rats (Mintz et al., 1986; Ni et al., 2001). We have recently carried out preliminary studies indicating that activation of D1LRs or D2LRs in the monkey STN increases the firing rates of STN neurons, and that D1LR activation decreases bursting activities of these neurons (Rommeffanger et al., 2010).

The discrepancy between studies demonstrating inhibitory and facilitatory effects of dopamine in the STN may in part be explained by differences in the location of the recorded neurons within the STN, the choice of anesthetics, or the pharmacological properties of the drugs used in these studies. For example, dopamine binds with higher affinity to D3-, D4-, and D5-receptors than to D1-receptors (Sunahara et al., 1991; Missale et al., 1998), and SKF38393 is a partial rather than full agonist at D1LRs (Twery et al., 1994; Kreis et al., 1996; Gleason and Witkin, 2004), complicating the interpretation of some of the earlier studies.

Studies of behavioral effects

Few studies have investigated the behavioral effects of dopamine receptor ligands in the STN. The available studies suggest that agents acting at D1LRs have stronger behavioral effects than agents acting at D2LRs. Activation of D1LRs in the STN resulted in orofacial dyskinesias in normal and dopamine-depleted rats (Parry et al., 1994; Mehta et al., 2000). In normal animals, bilateral STN infusions of D1LR- but not D2LR antagonists induced catalepsy in one study (Hauber, 1998). No such information is available from primate experiments.

INTERNAL PALLIDAL SEGMENT

Anatomical studies

GPI activity is indirectly under the control of dopamine released in the striatum, via the direct and indirect pathways. In addition, the primate GPI receives its own diffusely arborizing dopaminergic input (Parent and Smith, 1987; Lavoie et al., 1989; Parent et al., 1989; Hedreen, 1999), as demonstrated through the detection of dopamine in GPI (Piff et al., 1990; Hornykiewicz, 1998), by the presence of DAT in ligand binding studies, and through immunohistochemical investigations on human postmortem tissue (Marcusson and Eriksson, 1988; Ciliax et al., 1999; Porritt et al., 2005), monkey (Gnanalingham et al., 1995) GPI and in the rodent entopeduncular nucleus, the rat homologue to the monkey GPI (Ciliax et al., 1995; Coulter et al., 1995). Retrograde and anterograde tract tracing studies in rodents and monkeys have demonstrated that dopaminergic terminals in GPI do not arise from collaterals of the nigrostriatal tract, but from a separate population of SNc neurons that directly innervate the GPI (Fallon and Moore, 1978; Lindvall and Bjorklund, 1979; Smith et al., 1989; Parent et al., 1990; Schneider and Dacko, 1991; Gauthier et al., 1999; Jan et al., 2000).

Most of the available evidence suggests that dopaminergic effects in GPI are primarily mediated via D1LRs (Table 1). In rats, D1LR binding (Fremeau Jr. et al., 1991) and D1-receptor protein (Levey et al., 1993; Yung et al., 1995) were found in the entopeduncular nucleus (the rat homologue to the monkey GPI), predominately at presynaptic locations, on axons and putatively GABAergic terminals. In primates, receptor binding studies have demonstrated the presence of D1LRs in GPI (Richfield et al., 1987; Besson et al., 1988), which was recently confirmed by our ultrastructural studies (Kliem et al., 2010). Most of the D1- and D5-receptor labeling was found in unmyelinated pre-terminal axons, with additional postsynaptic D5-receptor labeling in dendrites and glial processes in rodents and monkeys (Ciliax et al., 2000; Kliem et al., 2010).

Receptor binding studies have demonstrated that the level of D2LRs is much lower than that of D1LRs in the primate GPI (Richfield et al., 1987; Besson et al., 1988). D3-receptor binding (but not mRNA) was also demonstrated in the monkey GPI (Quik et al., 2000), and D2- and D3-receptor mRNA and binding sites have been identified in the human GPI (Gurevich and Joyce, 1999). Studies in rats and monkeys have documented D4-receptor protein in the GPI (Mrzljak et al., 1996; Rivera et al., 2003). Using electron microscopy, we recently found that D2-receptors in the monkey GPI are almost exclusively presynaptic, with some receptors at presumably glutamatergic (i.e., forming asymmetric synapses) terminals (unpublished observations). Experiments in D2-receptor knockout mice have suggested that at least some of the presynaptic D2-receptors are...
autoreceptors (Mercuri et al., 1997; Koeltzow et al., 1998). Presynaptic D4-receptors in the rat entopeduncular nucleus may be located on GABAergic striatopallidal terminals (Rivera et al., 2003).

**Functional studies**

Overall, dopamine appears to decrease the neuronal activity in the GPi, likely via activation of D1LRs (Table 2). We found that microinjections of a D1LR agonist into the monkey GPi reduces GPi firing rates, and increases neuronal burst discharges and oscillatory firing in the 3–15 Hz range of frequencies. Interestingly, blockade of D1LRs in these studies resulted in increased spontaneous neuronal activity, suggesting that the D1LRs are occupied by endogenous dopamine under normal conditions (Kliem et al., 2007a). Because most D1LRs are found presynaptically on putatively GABAergic terminals (see above), it is likely that the D1LR agonist infusions into Gpi acted through a facilitation of GABA release. Microdialysis studies have shown, in fact, directly shown that GABA levels in the entopeduncular nucleus (in rats) or GPi (in monkeys) increase in response to activation of D1LRs (Freire et al., 1996; Kliem et al., 2007a), and that GABA release is reduced upon D1LR antagonist administration (Floran et al., 1990). Increased GABA levels may act to hyperpolarize GPi cells, lowering GPi firing and triggering rebound bursts, as in GPe and STN (Nambu and Llinas, 1994; Overton and Greenfield, 1995; Beurrier et al., 1999; Bevan et al., 2002; Kass and Mintz, 2006). The source(s) of the GABAergic inputs whose activity is regulated via D1LRs in GPi is not entirely certain, but it is likely that these fibers originate largely from the striatal medium spiny neurons that give rise to the direct pathway. Activation of postsynaptic D5-receptors and subsequent activation of GPi cells may also occur, counteracting some of the changes in GABA release induced by presynaptic D1LR activation.

There is relatively little evidence supporting D2LR-mediated effects in GPi. Peripheral administration of D2LR agonists decreases neuronal firing in human GPi cells (Hutchinson et al., 1997). Peripheral exposure to D2LR antagonists increases Fos-like immunoreactivity in the entopeduncular nucleus in normal rats (Wirtshafter and Asin, 1995), and reduces firing abnormalities in the entopeduncular nucleus in parkinsonian animals (Ruskin et al., 2002). It is likely that these drug effects are in large part secondary to activation or inactivation of striatal D2LRs, and are transmitted to GPi via the indirect pathway. In our recent experiments in monkeys, local activation of D2LRs in the GPi also resulted in decreased firing rates (Hadipour Niktarash et al., 2008), and blockade of these receptors increased firing rates (unpublished observations). The results of these local microinjection studies can perhaps be explained through activation of presynaptic D2LRs on glutamatergic terminals, although other mechanisms of action cannot be excluded.

**Studies of behavioral effects**

Very few studies have examined the behavioral effects of dopamine receptor activation in the GPi. Studies in human subjects have indicated that decreased dopamine levels in GPi, as measured with raclopride displacement positron emission tomography (PET), were associated with faster motor learning (Garraux et al., 2007). Studies using (18)F-DOPA PET in patients with PD suggested that pallidal (18)F-DOPA uptake may be increased in early stages of the disease, perhaps as a compensatory change (Whone et al., 2003).

**SUBSTANTIA NIGRA PARS RETICULATA**

**Dopamine release in the SNr**

Studies in the 1970s showed that dopamine release in the substantia nigra differs from that in the other basal ganglia nuclei in that the release is dendritic, rather than axonal (Korf et al., 1976; Leivel et al., 1979). Dendrites of SNc neurons may supply dopamine to SNr neurons from up to several hundred microns away, (Bjorklund and Lindvall, 1975; Nieoullon et al., 1978; Arsenault et al., 1988; Hausser et al., 1995). There continues to be debate regarding some of the characteristics of dendritic dopamine release. For instance, some studies have documented that dendritic release can be reduced by blockade of sodium channels with tetrodotoxin (Araneda and Bustos, 1989; Santiago and Westerink, 1991; Westerink et al., 1994; Cragg and Greenfield, 1997), and increased by depolarizing agents (Rice et al., 1994), and that release is calcium-dependent (Ford et al., 2010), suggesting that it may be mediated by action potentials. However, other authors concluded that the dendritic release of dopamine in the SNr is independent of action potentials (Robertson et al., 1991) and not stimulated by amphetamine (Bernardini et al., 1991; Robertson et al., 1991; Hoffman and Gerhardt, 1999; Gerhardt et al., 2002).

Another area of disagreement pertains to the question whether nigral dopamine release is vesicular. Early studies did not identify storage vesicles for dopamine in SNc dendrites (Reubi and Sandri, 1979; Wassef et al., 1981), but more recent studies have reported otherwise. Pleomorphic vesicles have been detected in the symmetrical dendrodendritic synapses of SNc neurons (Groves and Linder, 1983) and have been shown more recently to express the vesicular monoamine transporter (Nirenberg et al., 1996). Vesicular storage of dopamine at the level of the SN is also supported by evidence that the nigral release of dopamine is sensitive to reserpine, a compound that depletes vesicular dopamine pools (Elverfors et al., 1997), as well as compounds that interfere with vesicular fusion and release (i.e., the 25 kDa synaptosome-associated protein SNAP-25; Bergquist et al., 2002). In addition, dendritic dopamine signaling can be terminated via the DAT as DAT blockade can enhance nigral dopamine levels (Robertson et al., 1991; Santiago and Westerink, 1992; Cragg et al., 1997; Cragg et al., 2001). Dendritic DAT immunoreactivity in SNc and SNr has been detected in rodent (Nirenberg et al., 1996) and human tissue (Ciliax et al., 1999).

**Anatomical studies**

Receptor binding studies (Richfield et al., 1987) and immunohistochemical studies of the distribution of dopamine receptor protein (Levey et al., 1993; Yung et al., 1995; Kliem et al., 2010) have shown that the rat and monkey SNr contains predominantly pre- and postsynaptic D1LRs (Table 1). D1-receptor immunoreactivity associated with the SNr was shown to extend into the ventral SNc (Yung et al., 1995). These receptors have been described as being expressed mostly on putative GABAergic terminals of the direct striatonigral pathway (Levey et al., 1993; Bergson et al., 1995; Yung et al., 1995; Caille et al., 1996; Kliem et al., 2010), supported by the finding that striatal lesions reduce or abolish D1LR binding in the SNr (Beckstead, 1988; Berger et al., 1991). Postsynaptic D1-receptor localization has been suggested, on the basis of the detection of D1-receptor mRNA (Fremeau Jr. et al., 1991). D5-receptors have also been identified in rodents and monkeys in postsynaptic locations (Ciliax et al., 2000; Khan et al., 2000; Kliem et al., 2010).
There are fewer reports of D2LRs in the SNr (Table 1). D2-receptor protein has been identified in neurons in the ventral SNr in rats (Yung et al., 1995). Furthermore, mRNA distribution and receptor binding studies have shown D2- and D3-receptors in human SNr neurons (Gurevich and Joyce, 1999). D2-receptors were also detected in cell bodies and dendrites of SNc neurons extending into the SNr (Yung et al., 1995) suggesting that D2 autoreceptors in the SNc may regulate dopamine release within the SNr. We have recently demonstrated the presence of presynaptic D2-receptors in the monkey SNr on putatively GABA- and glutamatergic synapses (unpublished observations). In addition, D4-receptor protein has been identified with electron microscopy in neurons of the monkey SNr (Mrzljak et al., 1996), and at pre- and postsynaptic locations in the rat SNr (Rivera et al., 2003).

**Functional studies**

Most of the available studies in rodents agree that dopamine in the SNr acts primarily at presynaptic D1LRs, and that activation of these receptors reduces SNr firing via facilitation of GABA transmission from striatonigral (i.e., direct pathway) fibers (Table 2). Our recent primate recording experiments have confirmed that the local activation of D1LRs in the SNr reduces the activity of SNr neurons (Kliem et al., 2007a). Furthermore, local D1LR activation influenced the discharge patterns of SNr neurons, increasing oscillations in the low frequency ranges (3–15 Hz range of frequencies) and increasing bursting (Kliem et al., 2007a,b), perhaps through the induction of rebound bursts due to GABA-mediated hyperpolarization of SNr cells, as has been demonstrated to occur in GP and STN (Nambu and Llinas, 1994; Overton and Greenfield, 1995; Beurrier et al., 1999; Bevan et al., 2002; Kass and Mintz, 2006). Increased GABA release upon activation of D1LRs was shown in microdialysis studies, and is also supported by electrophysiologic experiments (Floran et al., 1990; Timmerman and Westerink, 1995; Rosales et al., 1997; Radnikow and Misgeld, 1998; Matuszewich and Yamamoto, 1999; Trevitt et al., 2002; Acosta-Garcia et al., 2009). Although it has also been shown that endogenous dopamine inhibits SNr neurons in anesthetized (Timmerman and Abergrombie, 1996) and awake, behaving rats (Windels and Kiyatkin, 2006), we did not find convincing pharmacological evidence for a significant dopaminergic “tone” in our recent primate experiments (Kliem et al., 2007a; unpublished observations).

Not all studies have agreed that the activation of D1LRs increases GABA release and reduces the activity of neurons in the SNr. Presynaptic inhibition of GABA release upon exposure to D1LR agonists was seen by some authors (Martin and Waszczak, 1994; Miyazaki and Lacey, 1998). These data corroborate previous in vivo studies in which the activity of SNr neurons was increased by iontophoretic application of D1LR agonist in anesthetized rats (Waszczak, 1990). It is possible that some of these excitatory effects of D1LR agonists arose from actions at non-GABAergic sites. For example, there is evidence that D1LR activation in the SNr may increase glutamate released by terminals originating from the STN (Rosales et al., 1997; Ibanez-Sandoval et al., 2006). It remains unclear why such effects were not seen in other studies.

In contrast to the large body of evidence describing the effects of D1LR activation in the SNr, there are few studies examining the effects of D2LR activation. These studies have come to contradictory conclusions (see Table 2). In rodents local application of agonists at D2LRs was shown to block the inhibitory effects of striatal stimulation on SNr neurons (Waszczak, 1990; Martin and Waszczak, 1996) and to reduce GABA release (Matuszewich and Yamamoto, 1999). Other studies have shown that activation of nigral D4-receptors inhibits dopamine-induced GABA release in rat brain slices, an effect that was reversed by lesions of the pallidum (Acosta-Garcia et al., 2009). In contrast, we have recently found that injections of the D2LR agonist quinpirole decreases firing rates of neurons in the monkey SNr, which may be explained through an inhibitory effect on glutamatergic afferents from the STN (Hadipour Niktarash et al., 2008).

There is also limited evidence that dendritic dopamine release may inhibit SNc neuron activity, and may, thus, indirectly affect dopamine release in the striatum, presumably resulting in secondary effect on the basal ganglia via direct and indirect pathways (Lacey et al., 1987; Pucak and Grace, 1994).

**Studies of behavioral effects**

The activation of dopamine receptors in the rat SNr has been shown to increase movement. Thus, infusions of agonists at D1LRs into the rodent SNr result in increased movement, drug-seeking behaviors, and an enhanced startle response (Meloni and Davis, 2004). Bilateral infusions of D1LR antagonists into the SNr were also shown to decrease lever-pressing and general locomotor activity (Jackson and Kelly, 1983a,b; Kelly et al., 1987; Trevitt et al., 2001), while unilateral injection of the D1LR antagonist inhibited amphetamine-induced stereotypies (Yurek and Hipkens, 1993; Lee et al., 1995; Timmerman and Abergrombie, 1996) and induced contralateral circling (Asin and Montana, 1988). In contrast, D1LR and D2LR antagonists impaired rod-balancing performance in normal rats (Bergquist et al., 2003). Irreversible blockade of dopamine receptors in the rat SNr was shown to increase electromyographic (EMG) activity and may contribute to the development of rigidity in parkinsonism (Crocker, 1995; Hemsley and Crocker, 1998) likely mediated via effects on D1LRs (Hemsley and Crocker, 2001). Depletion of dopamine release from SNc neurons through local intranigral administration of the VMAT2 inhibitor tetrahydrazine was shown to impair motor performance in rats without altering striatal dopamine release (Andersson et al., 2006).
GPe
Loss of the nigropallidal projection has been demonstrated in patients with PD and in animal models of the disorder (Jan et al., 2000). The nigropallidal system may be more strongly affected in MPTP-treated vervet monkeys (Bergman et al., 1994; Jan et al., 2000) than in MPTP-treated macaques (Parent et al., 1990; Schneider and Dacko, 1991). This difference may contribute to the differences in the sensitivities of these species to the effects of MPTP (Pifl et al., 1992). Intra-pallidal infusions of dopamine were shown to partially restore motor deficits in rats whose midbrain dopaminergic system was damaged through infusions of 6-hydroxydopamine (6-OHDA) into the medial forebrain bundle (Galvan et al., 2001). Interestingly, despite the predominance of D2LRs in the GP, intra-pallidal injections of agonists at D2LRs had no effect (El-Banoua et al., 2004). In 6-OHDA-treated rats, grafts of fetal mesencephalic cells into the GP were shown to result in behavioral recovery (Bartlett and Mendez, 2005).

SUBTHALAMIC NUCLEUS
There is substantial dopamine loss in the STN in MPTP-treated monkeys (Pifl et al., 1990; Rommelfanger et al., 2010) and in human PD patients (Hornykiewicz, 1998) which may contribute to the expression of motor signs. In addition, unilateral 6-OHDA lesions of the rat STN may result in contralateral muscle rigidity (Flores et al., 1993).

Recent studies in rodent brain slice preparations have suggested that the reduction of dopaminergic transmission in the parkinsonian state results in a lack of activation of D2LRs and D1-receptors which, in turn, contributes to the development of irregular discharges in the STN (see section on STN above). As D5-receptors are constitutively active, even in the absence of dopamine (Tiberi and Caron, 1994; Demchyshyn et al., 2000), D5-receptor activation in the dopamine-depleted state may contribute to the development of burst discharges in the STN (Baufreton et al., 2005b), a feature of parkinsonism in monkeys (Bergman et al., 1994) and humans (Hutchison et al., 1998).

The STN may be a target for dopaminergic drug treatments. For instance, intra-STN infusions of D1LR agonists reduced the motor asymmetry in rats with ipsilateral 6-OHDA lesions of the SNr (El-Banoua et al., 2004). The contribution of D5-receptor activation to neuronal bursting in the STN has been exploited in recent experiments in which the dopamine receptor antagonist flupenthixol reduced bursting activities of STN neurons in the dopamine-depleted state, presumably through actions on constitutively active D5-receptors (Cherit et al., 2010).

Transplantation of dopaminergic tissue or stem cells into the STN alone (Anderson and Caldwell, 2007) or in combination with striatal or nigral transplants has resulted in improved forepaw use or rotational behaviors in dopamine-depleted rats (Mukhida et al., 2001; Pavon-Fuentes et al., 2002; Inden et al., 2005), although this effect has been questioned by others (Pavon-Fuentes et al., 2002). The behavioral studies exploring the effects of injections or tissue grafts in rodents need to be replicated in monkeys before firm conclusions regarding their significance can be drawn. Because of the very small size of the rat STN, agents or cells injected in this nucleus may inadvertently diffuse to the neighboring SNr. Other than the results listed above for the STN, there is little experience with the effects of stem cells into extrastriatal regions. Given the relatively low yield of dopaminergic cells from traditional graft sources, the use of higher yield stem cell therapies aimed at replacing dopamine in extrastriatal basal ganglia regions may be a worthwhile future clinical strategy.

GPI AND SNr
While there is evidence of dopamine loss in the GPi of humans with PD (Hornykiewicz, 1998) and of MPTP-treated monkeys (Pifl et al., 1990), the behavioral consequences of this loss are not fully understood. As mentioned above, PET studies in humans have suggested that dopamine loss in the GPi may be involved in some of the early compensatory changes in PD (Whone et al., 2003).

An involvement of dopamine loss in the substantia nigra is supported by experiments exploring the effects of nigral infusions of dopamine receptor antagonists or reductions of nigral dopamine release in rats (see section on SNr above). These studies have suggested that actions of dopamine in the SNr may be involved in the control of normal movement and in the early compensation for striatal dopamine loss (Andersson et al., 2006). This is also suggested by behavioral experiments described earlier in this review wherein dopamine receptor activation can facilitate movement in rodents. It is unclear whether such motor effects would also occur in primates, as the primate SNr is more strongly involved in non-motor rather than motor behaviors (Parent and Hazrati, 1994; Haber and Fudge, 1997; Middleton and Strick, 2002). However, intraventricular and intranigral infusions of glial derived nerve-growth factor (GDNF) were shown to reduce parkinsonian motor deficits in MPTP-treated monkeys, associated with increased dopamine levels in the SN and the GP, but not in the striatum (Gash et al., 1996). GDNF has been clinically tested, but the therapeutic value of the explored GDNF treatment strategies, specifically the chosen delivery method and targeting, remains controversial (Gill et al., 2003; Nutt et al., 2003; Slevin et al., 2005; Lang et al., 2006). It is perhaps worth noting that the available human studies have not specifically examined (in isolation) the use of GDNF in extrastriatal tissues.

Several groups have shown that intranigral grafts of embryonic mesencephalic tissue attenuate rotational behavior and other behavioral abnormalities in 6-OHDA-treated rats (Nikkhah et al., 1995a,b; Olsson et al., 1995; Yurek, 1997; Johnston and Becker, 1999; Mukhida et al., 2001; Palmer et al., 2001) and in MPTP-treated monkeys (Starr et al., 1999; Collier et al., 2002). Furthermore, dual intrastratal and intranigral grafts of fetal dopaminergic tissue in humans helped to improve parkinsonism in PD patients, although not with greater benefit than intrastratal grafts (Mendez et al., 2002).

EFFECTS OF CLINICALLY USED DRUG TREATMENTS AT EXTRASTRIATAL SITES
One of the factors that determines whether clinically used dopaminergic antiparkinsonian drugs act at basal ganglia sites outside of the striatum is the availability and functional integrity of dopamine receptors at these sites in the parkinsonian state. There are, in fact, some reports of changes in the density of extrastriatal dopamine receptors in parkinsonian animals and in patients with PD. For instance, altered D1LR- and D2LR binding has been demonstrated in the STN (Flores et al., 1999; Murer et al., 1999; Mehta et al., 2000) and SN (Narang and Wamsley, 1995). Furthermore, the fraction of membrane-bound D1LRs in SNr and GPI appears to increase in
dopamine-depleted animals (Kliem et al., 2010). In human studies, D1LR radioligand binding was decreased while the mRNA levels remained unchanged in the GPe (Hurley et al., 2001). Another study did not detect any changes in D1LR- or D2LR binding at these sites (Cortes et al., 1989).

There is little evidence that the function of D1LRs or D2LRs in the extrastriatal basal ganglia changes from the normal to the dopamine-depleted state. In our recent comparison of changes in neuronal firing rates and patterns in response to local administration of agonists at D1LRs or D2LRs in GPe, STN, GPi, and SNr, no response differences were detected between normal and parkinsonian animals (Kliem et al., 2010; unpublished observations). Taken together the extrastriatal basal ganglia could be targets for clinically used dopaminergic agonists, such as the commonly used agonists pramipexole and ropinirole. These D2LR-prefering agents may not only act in the striatum, but also at the level of the GPe or its afferents, and perhaps at glutamatergic synapses in GPe and SNr (see above). Activation of extrastriatal D2LRs may act to reduce the irregularity of neuronal firing (through actions in the STN) and the overall activity at the level of the basal ganglia output nuclei (through actions in SNr and GPi).

A more detailed understanding of the effects of extrastriatal dopamine activation could also lead to a better understanding of the mechanisms involved in the frequent non-motor side effects of D2LR agonist therapies, such as disturbances in the control of impulsivity (Isaias et al., 2008), fatigue or hallucinations (Stowe et al., 2008; Truong et al., 2008). Such effects are most likely due to striatal actions of these drugs; however, extrastriatal actions may also play a role. Thus, recent studies have suggested that the STN and probably other basal ganglia areas may be part of the circuitry regulating impulsivity (Uslaner and Robinson, 2006) and reward related behaviors (Baune et al., 2005; Joshua et al., 2009; Rouaud et al., 2010).

**CONCLUDING REMARKS**

It is now clear that not only the striatum, but also all of the extrastriatal basal ganglia nuclei receive dopaminergic projections. While biochemical studies have shown measurable dopamine levels in all of these nuclei, our pharmacological studies in monkeys found evidence for an endogenous tone only in GPe and GPi.

The signals carried by the dopaminergic fibers to the extrastriatal basal ganglia may overlap with those carried to the striatum, but are probably not identical with them. For instance, because the STN receives collaterals of the nigrostriatal projection, it can be expected that the dopaminergic inputs to this nucleus carry some of the same information that is also transmitted from the SNC to the striatum. In contrast, the GPe and to a much lesser extent, the GPe receives a dopaminergic projection that is separate from that terminating in the striatum so that the signals it receives may differ from those that reach the striatum. There may also be substantial heterogeneity within the nuclei themselves. Thus, in monkeys, histological studies have demonstrated dopaminergic inputs to the dorsal regions of GPe and STN, while more ventral portions of these nuclei may receive fewer (or no) dopaminergic inputs. The actual “reach” of dopamine, and the timing and strength of its effects within each of these nuclei will, of course, not only be determined by the anatomical innervation, but also by the range of diffusion. The factors influencing diffusion, in these nuclei such as the distribution and density of dopamine receptors, and the expression pattern and concentration of DAT are not sufficiently known at this time.

The large body of literature that is reviewed in this article demonstrates that virtually all of the dopamine receptor subtypes are expressed in each of the extrastriatal basal ganglia, albeit with different patterns of pre- or postsynaptic expression. With some exceptions, it appears that activation of D1LRs and D2LRs within the individual nuclei generates similar responses. For instance, our primate studies have demonstrated that activation of D1LRs in GPe and SNr leads to an inhibition of firing, most likely explained through increased GABA release in these nuclei. We also found that D2LR activation reduces neuronal activity in these nuclei, perhaps through reductions of glutamate release from STN inputs. Another example for the overall similarity of D1LR and D2LR activation would be the actions of dopamine in the STN. D1LR activation may increase the activity of STN neurons via postsynaptic effects, while D2LR activation could achieve the same effect through presynaptic inhibition of GABA release. The view that D1LR and D2LR effects are in some sense similar is obviously simplistic, but it may result in the recognition of overall response patterns of neurons in these nuclei to endogenous dopamine: the activity of GPe and SNR neurons appears to be increased, while the activity of the basal ganglia output nuclei, GPe and SNr, appears to be reduced.

As mentioned above, there is clear evidence that dopamine is lost at extrastriatal sites in PD, and it is possible that the loss of dopamine at these sites contributes to the development of some aspects of parkinsonism. While the behavioral effects of activation or blockade of dopamine receptors at extrastriatal sites still needs to be clarified, it is clear that dopamine receptor activation in all of the nuclei discussed have strong effects on neuronal activities, even in the parkinsonian state. It seems therefore likely that these receptors mediate some of the beneficial and adverse effects of commonly used antiparkinsonian dopamine receptor agonist regimens.

In practical terms, the knowledge regarding dopaminergic effects at extrastriatal sites could be used for site-specific dopaminergic therapies in PD patients. By targeting some of the known key steps in the pathophysiology of PD, some of the well-known side effects of existing dopaminergic treatments could potentially be avoided. For instance replacement of dopamine in STN or GPe may help us to reduce neuronal bursting activities, while replacement of dopamine in GPe or SNr could reduce overall basal ganglia output. Given the ubiquitous presence of dopamine receptor subtypes in the striatum and extrastriatal basal ganglia, it will be challenging to devise systemic pharmacological treatments to achieve dopaminergic effects at specific basal ganglia locations. However, such specificity could be achieved by surgical procedures to re-establish dopaminergic stimulation in specific basal ganglia nuclei, through grafting, stem cell therapies, viral transfection methods, or even some of the newly developed optogenetic approaches targeting G-protein coupled receptors (Airan et al., 2009). Thus, understanding the functions of extrastriatal dopamine could not only provide a more comprehensive view of the role of dopamine in the basal ganglia, but also may prove therapeutically fruitful in the long-term.
REFERENCES


Hauber, W., and Lutz, S. (1999). Dopamine D1 or D2 receptor blockades in the globus pallidus produces akinesia in the rat. Behav. Brain Res. 106, 143–150.


Kita, H., Nambu, A., Kaneda, K., Tachibana, Y., and Takada, M. (2004). Role of ionotropic glutamatergic and GABAergic inputs on the firing activity...


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