Perspectives in Pharmacology

Striatal α6* Nicotinic Acetylcholine Receptors: Potential Targets for Parkinson’s Disease Therapy

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ABSTRACT

The presence of distinct nicotinic acetylcholine receptor (nAChR) subtypes in specific central nervous system (CNS) areas offers the possibility of developing targeted therapies for diseases involving the affected brain region. Parkinson’s disease is a neurodegenerative movement disorder characterized by a progressive degeneration of the nigrostriatal system. α6-containing nAChRs (designated α6* nAChRs) have a relatively selective localization to the nigrostriatal pathway and a limited number of other CNS regions. In addition to a unique distribution, this subtype has a distinct pharmacology and specifically interacts with α-conotoxinMII, a toxin key in its identification and characterization. α6* nAChRs are also regulated in a novel manner, with a decrease in their number after nicotine treatment rather than the increase observed for α4* nAChRs. Striatal α6* receptors were functional and mediate dopamine release, suggesting that they have a presynaptic localization. This is further supported by lesion studies showing that both α6* nAChR sites and their functions are dramatically decreased with dopaminergic nerve terminal loss, in contrast to only small declines in α4* and no change in α7* receptors. Although the role of nigrostriatal α6* nAChRs is only beginning to be understood, an involvement in motor behavior is emerging. This latter observation coupled with the finding that nicotine protects against nigrostriatal damage suggest that α6* nAChRs may represent unique targets for neurodegenerative disorders linked to the nigrostriatal system such as Parkinson’s disease.

Currently available therapeutics for Parkinson’s disease, a neurodegenerative disorder characterized by rigidity, tremor, and bradykinesia, include administration of the dopamine precursor L-dopa and/or dopamine agonists (Olanow, 2004; Samii et al., 2004). These drugs partially compensate for the decline in striatal dopamine that arises because of the loss of substantia nigra dopaminergic neurons. However, long-term dopamine replacement therapy leads to motor and psychiatric complications, and there is a loss of efficacy with time, probably because of disease progression. There is therefore an urgent need for novel therapeutics for better management of Parkinson’s disease.

Acetylcholine can also regulate striatal dopamine levels by stimulating nicotinic acetylcholine receptors (nAChRs). These receptors are localized on nigrostriatal dopaminergic nerve terminals where they control dopamine release (Wonnacott, 1997; MacDermott et al., 1999; Gotti and Clementi, 2004). Since striatal nAChRs seem to be involved in both motor control and neuroprotection against nigrostriatal damage (O’Neill et al., 2002; Quik, 2004), identification of the receptor subtypes is important for understanding basal ganglia function under physiological conditions and pathological states such as Parkinson’s disease.

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Abbreviations: nAChR, nicotinic acetylcholine receptor; CNS, central nervous system; MPTP, 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine.
tors composed of the human though not without difficulty (Kuryatov et al., 2000). Receptors containing only mammalian subunits was subsequently achieved, although it may be localized to other neuronal elements in different brain regions. The combination of a unique pharmacology and distribution may allow for selective therapeutic targeting of α6*-nAChRs for CNS disorders involving this subtype.

**Selective Interaction of α6*-nAChRs with α-ConotoxinMII**

Although evidence for receptors containing an α6 subunit was first reported in 1990 (Lamar et al., 1990), several years elapsed before α6* receptor characteristics were described primarily because of difficulties in their expression and identification (Gerzanich et al., 1997; Fucile et al., 1998; Kuryatov et al., 2000). Functional α6* nAChRs expression was first achieved in oocytes with the chick 6 and human β4 subunits (Gerzanich et al., 1997) and later in human BOSC 23 cells with a purely avian α6β4* nAChR (Fucile et al., 1998). The chick α6 subunit also formed functional heteromeric nAChR with chick β2, although at a much lower abundance (Fucile et al., 1998). Functional expression of an α6* nAChR composed of only mammalian subunits was subsequently achieved, although not without difficulty (Kuryatov et al., 2000). Receptors composed of the human α6 and β4 subunits expressed only poorly in oocytes, whereas injection of α6 with β2 resulted in the formation of nonfunctional epibatidine binding aggregates; however, functional human α6β4β3, as well as α6β2α5 nAChRs, were observed (Kuryatov et al., 2000). Efficient expression was obtained when the N-terminal extra-

cellular portion of α6 was joined to the remaining portions of either α3 or α4 and expressed with either the β2 or β4 subunits (Kuryatov et al., 2000; Dowell et al., 2003; Evans et al., 2003). Furthermore, the addition of the β3 subunit significantly improved expression of these chimeric α6*-receptors (Dowell et al., 2003). Altogether, these data show that α6 subunits can assemble in heterologous expression systems with the β2 or β4, as well as the α5 and β3, subunit.

A striking pharmacological feature of α6* nAChRs is their high-affinity interaction with the naturally occurring snail toxin α-conotoxinMII (Kuryatov et al., 2000; McIntosh et al., 2004). This toxin binds to α6* nAChRs in a slowly reversible manner, which makes it a useful ligand for receptor identification and characterization. Indeed, receptor studies with [125I]α-conotoxinMII demonstrated a high-affinity (Kd, ~0.8 nM) nAChR in rodent, monkey, and human brain (Whiteaker et al., 2000; Quik et al., 2001; Quik et al., 2004). In addition, α-conotoxinMII also potently interacts with α3* nAChRs because of the high sequence homology to the α6 subunit (~75%). This presents a problem for receptor identification in tissues that contain both of these subtypes and has led to a search for compounds that can distinguish between α3* and α6* nAChRs (Table 1). One such agent is α-conotoxin PIA, a toxin from *Conus purpureascens*, which is ~75-fold more selective for heterologously expressed chimeric α6/α3β2* versus α3β2 nAChRs (Dowell et al., 2003). α-ConotoxinMII analogs exhibited an even greater selectivity (up to 2000-fold) for α6* compared with α3* nAChRs (McIntosh et al., 2004). The IC50 values of these peptide analogs for chimeric α6β2* nAChRs in functional assays are all in the picomolar to nanomolar range and correlate well with those obtained from [125I]α-conotoxinMII competition binding assays in mouse striatum (Fig. 1) that contains α6* and not α3* nAChRs (Whiteaker et al., 2002; Champniaux et al., 2003; McIntosh et al., 2004).

It is worth noting that α-conotoxinMII-sensitive α6* receptors also have high affinity for methyllycaconitine, a plant alkaloid historically considered selective for α7 nAChRs. Putative α6α4α5β2 nAChRs present on dopamine neurons in rat substantia nigra and ventral tegmental area are completely inhibited by 1 nM methyllycaconitine (Klink et al., 2001). Moreover, data from knockout mice suggest that these α-conotoxinMII- and methyllycaconitine-sensitive nAChRs do not contain α7 subunits (Klink et al., 2001). Methyllycaconitine is also a potent inhibitor of α-conotoxinMII-sensitive-mediated dopamine release in striatum (Mogg et al., 2002; Karadheh et al., 2004). Thus, methyllycaconitine potently interacts with both α7 and α6* nAChRs.

**TABLE 1**

<table>
<thead>
<tr>
<th>α-Conotoxin selectivity for α6β2* vs. α3β2* nAChRs</th>
</tr>
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<tbody>
<tr>
<td>Subtype selectivity was evaluated from functional studies using rat nAChR subtypes expressed in oocytes and/or from binding assays using mouse brain membranes. The peptides are named according to the residues substituted; for instance, MII [H9A] has the histidine in position 9 substituted with alanine. Where tested, all α-conotoxins demonstrated at least a 100-fold preference for α6 and/or α3 over other α subunit-expressing nAChRs (α1, α2, α4, and α7).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>α-Conotoxin</th>
<th>α-Conotoxin Sequence</th>
<th>-Fold Preference of α6β2 &gt; α3β2</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>GIC</td>
<td>GCCSRPACAGNNQHIC</td>
<td>α6 ~ α3</td>
<td>McIntosh et al. (2002)</td>
</tr>
<tr>
<td>PIA</td>
<td>RDPCGNSNPCITVNPQIC</td>
<td>~75</td>
<td>Dowell et al. (2003)</td>
</tr>
<tr>
<td>MII</td>
<td>GCCSNPVCHLEHSHNL</td>
<td>~3 to 6</td>
<td>Cartier et al. (1996); Dowell et al. (2003); McIntosh et al. (2004)</td>
</tr>
<tr>
<td>MII [H9A]</td>
<td>GCCSNPVCHLEHSHNL</td>
<td>~75</td>
<td>McIntosh et al. (2004)</td>
</tr>
<tr>
<td>MII [L15A]</td>
<td>GCCSNPVCHLEHSHNL</td>
<td>~40</td>
<td>McIntosh et al. (2004)</td>
</tr>
</tbody>
</table>
 Altogether, these results show that \( \alpha^6 \) nAChR receptor sites represent a class of neuronal nAChRs with a unique pharmacological profile. Moreover, \( \alpha \)-conotoxinMII and related peptides from Conus seem to be excellent tools to investigate their characteristics and function.

### Selective CNS Distribution of \( \alpha^6 \) nAChRs

**mRNA Studies**

mRNA localization studies show that the \( \alpha^6 \) nAChR transcript exhibits a very restricted distribution in rodent and monkey brain (Table 2). \( \alpha^6 \) mRNA labeling is particularly strong in catecholaminergic nuclei, including the substantia nigra, ventral tegmental area, and locus coeruleus, as well as in the medial habenula and interpeduncular nucleus, with a less intense signal in other brain nuclei (Le Novere et al., 1996; Han et al., 2000; Quik et al., 2000; Azam et al., 2002; Champtiaux et al., 2002). The distribution of \( \alpha^6 \) mRNA coincides with that of \( \beta^3 \) mRNA in the substantia nigra and ventral tegmental area (Table 2), suggesting that these transcripts are expressed in parallel in dopaminergic neurons (Azam et al., 2002).

**Receptor Studies**

\( \left[^{125}\text{I}\right] \alpha \)-ConotoxinMII selectively and saturably binds to nAChRs in neuronal pathways expressing \( \alpha^6 \) mRNA. This includes the substantia nigra and ventral tegmental area, as well as their projection areas, the striatum and nucleus accumbens. \( \alpha \)-ConotoxinMII-sensitive receptors are also present in the mediobasal hypothalamus, interpeduncular nucleus, and regions associated with the visual system in both rodent and monkey brain (Whiteaker et al., 2000; Quik et al., 2001; Champtiaux et al., 2002).

Since \( \alpha \)-conotoxinMII interacts with \( \alpha^6 \) and \( \alpha^3 \) nAChRs in heterologous expression systems, the question arises whether the toxin binds to both of these subtypes in mammalian brain. Studies with nAChR subunit knockout mice showed that \( \left[^{125}\text{I}\right] \alpha \)-conotoxinMII binding was not significantly decreased in striatum of \( \alpha^3 \) (\( -/- \)) mouse but was virtually eliminated in \( \alpha^6 \) (\( -/- \)) mice, suggesting that the toxin binds to only \( \alpha^6 \) nAChRs in mouse striatum (Champtiaux et al., 2002; Whiteaker et al., 2002). \( \left[^{125}\text{I}\right] \alpha \)-ConotoxinMII binding was also abolished in other brain regions of \( \alpha^6 \) (\( -/- \)) mice but only partially reduced in the medial habenula and interpeduncular nucleus. In addition, \( \left[^{125}\text{I}\right] \alpha \)-ConotoxinMII was partially decreased in these latter regions in \( \alpha^3 \) (\( -/- \)) mice and unchanged in striatum and other regions. Altogether, these data indicate that \( \left[^{125}\text{I}\right] \alpha \)-ConotoxinMII binds to both \( \alpha^6 \) and \( \alpha^3 \) receptors in the medial habenula-interpeduncular pathway but only to \( \alpha^6 \) sites in striatum and other CNS regions in mouse brain. A different situation seems to exist in the primate CNS. Immunoprecipitation studies with subunit-targeted antibodies showed that there was appreciable \( \alpha^6 \) subunit-like immunoreactivity in monkey striatum, as well as a smaller \( \alpha^3 \) signal (Quik et al., 2005b). To conclude, only \( \alpha^6 \) nAChRs are detectable in rodent striatum, whereas both \( \alpha^6 \) and \( \alpha^3 \) nAChRs are localized in primate striatum.

**Composition of \( \alpha^6 \) nAChRs in Striatum**

To identify the subunit composition or other subunits co-expressed with \( \alpha^6 \), antibodies targeted to specific nAChR subunits have been used (Zoli et al., 2002; Champtiaux et al., 2003; Gotti et al., 2005). They also show the presence of \( a_4 \), \( a_5 \), \( a_7 \), \( \beta_2 \), \( \beta_3 \), and \( \beta_4 \) but not \( \alpha_2 \) subunits in rodent striatum (Zoli et al., 2002; Champtiaux et al., 2003; Gotti et al., 2005). Similar studies using primate striatal tissue indicate there are species differences in nAChR subunit expression between monkeys and rodents. Both the \( \alpha_3 \) and \( \alpha_6 \) subunits were identified in monkey striatum, as well as \( a_2 \), \( a_4 \), \( a_7 \), \( \beta_2 \), and \( \beta_3 \), but not the \( \alpha_5 \) and \( \beta_4 \) subunits.

Dual-label immunoprecipitation shows that the subtypes common across species are \( \alpha_6\beta_2\gamma_3 \) and \( \alpha_6\beta_3 \), as well as \( \alpha_4\beta_2 \) and \( \alpha_7 \) receptors (Fig. 2A; Table 3) (Zoli et al., 2002;
Champtiaux et al., 2003; Gotti et al., 2005; Quik et al., 2005b). In addition, there also seems to be a population of less abundant striatal nAChR subtypes that are unique to different species (Table 3). To date, these include α4β5δ2 receptors on dopamine terminals in mouse but not monkey (Zoli et al., 2002; Champtiaux et al., 2003) and α3β2* receptors present in monkey but not mouse (Quik et al., 2005b). Identification of the precise mix of nAChR subtypes in striatum is important because it may allow for selective targeting with drugs that uniquely interact with these populations.

Striatal α6 nAChR Stimulation and Dopamine Release

Studies to evaluate the role of α6β2* nAChRs have focused on mammalian striatum because of the relatively high receptor density, the availability of assays to study their function, and putative links to addiction and neurodegenerative disorders. An approach that has proved particularly useful for studying function of striatal nAChRs is nicotine-evoked dopamine release. Stimulation of presynaptic striatal nAChRs results in dopamine release that is mediated by subtypes that are blocked by α-conotoxinMII and those that are not (Grady et al., 2002). In rodents, α-conotoxinMII-sensitive dopamine release is most likely mediated through α6β2* nAChRs and represents ~40% of the total response (Kulak et al., 1997; Kaiser et al., 1998; Salminen et al., 2004b), whereas α-conotoxinMII-resistant release occurs through α4β2* nAChRs and represents ~60% of the response (Fig. 3).

This conclusion is supported and extended by findings from nAChR knockout mice. Total nicotine-stimulated dopamine release is eliminated in β2 (−/−) mice, indicating an absolute requirement for the β2 subunit (Champtiaux et al., 2003; Salminen et al., 2004b). Evoked release is also abolished in double knockout α4 (−/−) α6 (−/−) mice and significantly affected in α4 (−/−) or α6 (−/−) mice, suggesting a mandatory presence for either the α4 or α6 subunit (Champtiaux et al., 2003; Salminen et al., 2004b). Results with α5 (−/−) and β3 (−/−) mice suggest a modulatory role for these subunits (Salminen et al., 2004b). In contrast, deletion of the β4 and α7 nAChRs had no effect on release. Since the α2 and α3 subunits are not present in mouse striatum, these combined results substantiate a role for receptors containing the α4, α5, α6, β2, and β3 nAChR subunits in nicotine-evoked dopamine release from mouse striatum (Cui et al., 2003; Salminen et al., 2004a; Gotti et al., 2005).

The use of α-conotoxinMII, coupled with nAChR knockout mice, has allowed for further identification of the receptors that mediate dopamine release. α-ConotoxinMII completely blocks nicotine-stimulated dopamine release in α4 (−/−) mice, showing that a component of release is mediated by α6* nAChRs (Salminen et al., 2004b). Conversely, α-conotoxinMII does not block residual dopamine release in α6 (−/−) mice, demonstrating an α6* nAChR-sensitive component (Champtiaux et al., 2003). Altogether, the above studies, coupled with immunoprecipitation data (Zoli et al., 2002; Champtiaux et al., 2003) and studies with α6*-selective conotoxins (McIntosh et al., 2004; Azam and McIntosh, 2005), suggest that α-conotoxinMII-sensitive sites in mice represent α6β2β3 and α6α4β2β3 subtypes, whereas α-conotoxinMII-resistant receptors are α4β2 and α4α5β2 nAChRs.

The situation in primate striatum bears resemblance and

![Fig. 2. Schematic representation (A) of the top view of the arrangement of putative neuronal nicotinic receptor subtypes common to rodent and monkey striatum. The closed diamond represents a recognition site with which both nicotine and α-conotoxinMII can interact, whereas the closed circle represents a site to which α-conotoxinMII does not bind. Schematic localization (B) of nAChR subtypes in the nigrostriatal pathway.](image-url)
some differences compared with rodents. In monkey striatum, the greater portion (70%) of nicotine-evoked dopamine release is mediated through α9β2*-conotoxinMII-sensitive (6%) and/or α3β2*-conotoxinMII-resistant (30%) subtypes, whereas α9β2*-conotoxinMII-resistant or α4β2*-receptors mediate only 30% release; these proportions were reversed in rodents (Fig. 3) (Kulak et al., 1997; Grady et al., 2002; McCallum et al., 2005a). The α9β2*-conotoxinMII-sensitive release most likely occurs in response to stimulation of α9β2* and/or α3β2* subtypes (Quik et al., 2005b) as in rodents, but in monkeys it may also involve α3β2* receptors.

Overall, there is a consensus that, in striatum, presynaptic α6*, as well as α4*, nAChRs play a critical role in receptor-evoked dopamine release with a greater contribution from α6* versus α4* nAChRs in primates than rodents. The localization and function of α6* nAChRs in the visual, habenular-interpeduncular, and other pathways remain to be investigated.

### Down-Regulation of α6* nAChRs with Long-Term Nicotine Treatment

Until fairly recently, there was a general consensus that nicotine treatment up-regulates nAChRs (Wonnacott, 1990; Gotti and Clementi, 2004). However, converging studies now suggest that this pertains primarily to α4β2* nAChRs. This is one of the most prevalent CNS subtypes, and effects on these sites may have masked changes in other populations.

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**TABLE 3**

<table>
<thead>
<tr>
<th>Species Comparison</th>
<th>nAChR Subtype</th>
<th>Presence in Striatum</th>
<th>Striatal Localization</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Similarities</strong></td>
<td>α6β2β3</td>
<td>Yes</td>
<td>Dopaminergic terminals</td>
<td>Zoli et al. (2002); Champtiaux et al. (2003); Gotti et al. (2005); Quik et al. (2005)</td>
</tr>
<tr>
<td></td>
<td>α6β2β3</td>
<td>Yes</td>
<td>Dopaminergic terminals</td>
<td>Zoli et al. (2002); Champtiaux et al. (2003); Quik et al. (2005)</td>
</tr>
<tr>
<td></td>
<td>α4β2</td>
<td>Yes</td>
<td>Dopaminergic terminals, other</td>
<td>Zoli et al. (2002); Champtiaux et al. (2003); Quik et al. (2005)</td>
</tr>
<tr>
<td></td>
<td>α7</td>
<td>Yes</td>
<td>Glutamatergic terminals, other</td>
<td>Zoli et al. (2002); Jones and Wonacott (2004); Gotti et al. (2005); Quik et al. (2005)</td>
</tr>
<tr>
<td><strong>Differences</strong></td>
<td>α4β2β2</td>
<td>Yes</td>
<td>Dopaminergic terminals, other</td>
<td>Zoli et al. (2002); Champtiaux et al. (2003)</td>
</tr>
<tr>
<td></td>
<td>α3β2β2*</td>
<td>No</td>
<td>Dopaminergic terminals, other</td>
<td>Quik et al. (2005)</td>
</tr>
<tr>
<td></td>
<td>α6β2β2*</td>
<td>No</td>
<td>Not known</td>
<td>Quik et al. (2005)</td>
</tr>
</tbody>
</table>

### Fig. 3.

Comparison of α6* and α4* nAChR-evoked dopamine release and receptor levels in monkey and mouse striatum. Nicotine-evoked [3H]dopamine release was done in the absence (total release) and presence of 50 nM α9β2*-conotoxinMII to distinguish release mediated by different nAChR subtypes. Release remaining in the presence of α9β2*-conotoxinMII, defined as α9β2*-conotoxinMII-resistant, is most likely mediated by α4* nAChRs; the difference between total and α9β2*-conotoxinMII-resistant [3H]dopamine release is defined as α9β2*-conotoxinMII-sensitive and represents release mediated by α6* nAChRs in mouse and by α6* and possibly α3* receptors in monkeys. Note the greater proportion of α6* nicotinic receptor-evoked dopamine release compared with that in response to α4* receptor activation. [125I]α9β2*-ConotoxinMII was used to label α6* nicotinic receptors, whereas α4* binding sites were determined using [125I]epibatidine in the presence of 100 nM α9β2*-conotoxinMII. These differences in function between monkeys and mice correlate with the α6* and α4* receptor levels in the two species.
Indeed, chronic nicotine administration does not alter α3β4* nAChRs in the central or peripheral nervous system (Flores et al., 1997; Davila-Garcia et al., 2003; Nguyen et al., 2003), whereas α7 nAChRs are generally unaffected and sometimes modestly increased across brain regions (Pauly et al., 1991, 1996). In contrast, recent studies indicate that α6* nAChRs are decreased in mouse striatum after several weeks of nicotine treatment administered via drinking water or by chronic jugular infusion (Salminen et al., 2004a; Lai et al., 2005). The reduced receptor number is associated with a decline in α6* nAChR-evoked [3H]dopamine release, indicating that the receptor loss is of functional significance (LSalminen et al., 2004a; ai et al., 2005). Although some studies have not reported a decline in α6* sites after nicotine treatment, this may relate to the route of administration, species, age, and/or method of α6* receptor determination (Nguyen et al., 2003; Parker et al., 2004).

Altogether, these findings show that nicotine treatment differentially influences nAChR subtypes, with increases, decreases, or no change. This disparate regulation suggests that distinct mechanisms control receptor expression. The increase in α4β2* sites may be due to nicotine-induced receptor desensitization that resembles an apparent receptor blockade, with a compensatory increase to ameliorate the functional loss. Nicotine may also decrease the turnover rate of already assembled nAChRs and/or act intracellularly on receptor precursors to enhance their maturation (Sallette et al., 2005). The down-regulation of α6* nAChRs with chronic nicotine treatment suggests that this subtype is controlled in a fashion analogous to that for neurotransmitter receptors that decrease with persistent agonist exposure (Creese and Sibley, 1981; Wonnacott, 1990). This differential control by nicotine may occur through an interaction with specific residues on the α subunits, comparable to the regulatory microdomains identified on the β2 versus β4 subunits (Sallette et al., 2004).

Overall, the presence of multiple nAChR populations, including α6α4β2β3, α6β2/3, α4β2, as well as α7 and possibly others (Fig. 1; Table 2), provides the potential for a complex regulation by nicotine in striatum. There may thus be widely divergent nAChR-mediated functional changes in striatum after nicotine exposure in smokers or individuals on chronic nicotine therapy.

### Loss of Striatal α6* nAChRs with Nigrostriatal Damage

Denervation studies are commonly used to investigate receptor localization and function. Lesion experiments involving α6* nAChRs have focused on the nigrostriatal system because of the availability of toxins that selectively destroy this pathway and the relevance to neurodegenerative disorders, such as Parkinson’s disease. Initial studies using monkeys lesioned with the selective dopaminergic neurotoxin 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine (MPTP) showed that there was a dramatic decline in [125I]α-conotoxinMII binding or α6* nAChRs, with a smaller loss of α4* nAChRs (Quik et al., 2001). The nAChRs declines correlated with those in the dopamine transporter, a marker of nerve-terminal integrity, suggesting that α6* receptors are located presynaptically. Experiments to investigate the link between lesion-induced receptor declines and function showed there was a regionally selective compensation in both α6* and α4* receptor-mediated [3H]dopamine release with nigrostriatal damage (McCallum et al., 2005a,b).

There was also a decline in nAChRs with nigrostriatal damage in rodents, but in this species there were similar losses in both α6* and α4* subtypes (Zoli et al., 2002; Champtiaux et al., 2003; Quik et al., 2003). Interestingly, striatal nAChR function in mice was not decreased until the dopamine transporter was reduced by ~20% (Quik et al., 2003), again suggesting some form of functional adaptation.

The results of lesion studies suggest that α6* nAChRs are localized to dopaminergic terminals in the striatum, with a loss of α6α4β2β3 and α6β2β3 nAChRs after nigrostriatal damage in both primates and rodents (Fig. 2B). These studies also showed declines in α4β2* nAChRs (Zoli et al., 2002; Champtiaux et al., 2003; Salminen et al., 2004b; Gottli et al., 2005; Quik et al., 2005b). These receptor losses seem to be biologically relevant, with a decline in dopamine release after nigrostriatal damage, although significant functional compensation occurred, particularly in primates. These adaptive mechanisms may be responsible, at least in part, for the observation that Parkinson’s disease symptoms only develop after >80% declines in striatal dopamine.

### α6* nAChRs in Human Brain: Declines in Parkinson’s Disease

Multiple nAChRs have been identified in human CNS, including α4*, α7*, and more recently α6* subtypes (Court et al., 2000; Gottli and Clementi, 2004; Quik, 2004). These latter studies show that [125I]α-conotoxinMII binds with high affinity (~0.5 nM) to numerous regions in human brain that include, in order of decreasing intensity of labeling, optic tract, nucleus accumbens, caudate, and putamen, consistent with results in rodents and primates (Quik, 2004; Bohr et al., 2005). In addition, [125I]α-conotoxinMII binding sites were identified in hippocampus, globus pallidus, frontal cortex, thalamus, and cerebellum, distinct from results in rodent and nonhuman primates. This may reflect binding to α3* nAChRs in human brain, although it is also possible that α6* nAChRs are present in these latter regions in humans. Such an interpretation is consistent with in situ hybridization results with α3-subunit mRNA probes, which identified the α3 transcript in the cortex, hippocampus, and thalamus (Rubboli et al., 1994; Guan et al., 2002). In addition, studies using α3-subunit directed antibodies show that α3-like immunoreactivity is present in these same regions (Guan et al., 2002).

Since the nigrostriatal pathway degenerates in Parkinson’s disease, the question arose whether α6* nAChRs are decreased as in experimental models. Indeed, there were 50 to 90% reductions in [125I]α-conotoxinMII sites in Parkinson’s disease striatum, the region containing dopaminergic nerve terminals (Quik et al., 2004; Bohr et al., 2005). In human brain, this decline in [125I]α-conotoxinMII binding did not parallel the dopamine nerve terminal loss as closely as anticipated, with greater losses of the transporter compared with nAChRs (Quik et al., 2004). These data suggest that [125I]α-conotoxinMII sites may be located both pre- and postsynaptically in human striatum.

The composition of [125I]α-conotoxinMII receptors, that is, whether they contain α3 and/or α6 subunits in human brain,
is currently not known. One study reported a decrease in α3-like immunoreactivity in Parkinson's disease striatum (Guan et al., 2002), although others found no change in α2–α7, β2, and β3 nAChR subunit immunoreactivity (Martin-Ruiz et al., 2002) despite undisputed declines in striatal nAChRs using radioligand binding studies. Thus, although there are clearly alterations in both α4* and α6*/α3 (α-conotoxinMII-sensitive) subtypes in Parkinson's disease striatum, their composition requires further study.

**Functional Consequence of Striatal α6 nAChR Stimulation**

nAChRs are important in a host of CNS functions, including learning, attention, addiction, reinforcement, and motor activity (Picciotto, 2003; Gotti and Clementi, 2004; Quik, 2004; Wonnacott et al., 2005). Although the specific nAChR subtypes remain to be elucidated, accumulating studies suggest a role for α4* nAChRs. In addition, the relatively dense distribution of α6* nAChRs in brain regions linked to these and other functions suggest this latter subtype may also play a role (Whiteaker et al., 2000; Quik et al., 2001; Moretti et al., 2004). For instance, α6* nAChRs in the optic tract and its target regions may be important in vision; the occurrence of α6* receptors in nucleus accumbens suggests a possible involvement in addiction, whereas their presence in striatum may imply a role in locomotor activity.

**Putative Symptomatic Effect of Nicotinic Receptor Stimulation on Motor Function**

Nicotine and nicotinic agonist administration has long been known to modulate movement in rodents (Picciotto, 2003). Extensive studies indicate a role for striatal α4* nAChRs, most likely through release of striatal dopamine (Grady et al., 1992; Wonnacott, 1997; Ryan et al., 2001). More recent experiments indicate that α6* subtypes may also be involved since nicotine-induced locomotor activity is attenuated in mice treated with α6 antisense (Le Novere et al., 1999). α6* nAChRs may represent a somewhat more selective target for modulating motor behaviors since these receptors exhibit a more restricted localization than the α4* subtype, which is widespread throughout the brain (Gotti and Clementi, 2004; Quik, 2004).

In neurodegenerative disorders such as Parkinson’s disease, there is a loss of presynaptic dopamine terminals and an accompanying decline in nAChRs (Quik et al., 2004; Bohr et al., 2005). This raises the possibility that stimulation of residual α6* (as well as α4*) nAChRs could enhance release from remaining terminals to result in symptomatic improvement in motor symptoms. A question that arises is how effective α6* (and/or α4*) nAChR stimulation is when studies show there is ~50 to 90% decline in the receptors in Parkinson’s disease striatum (Quik et al., 2004; Bohr et al., 2005). Interestingly, our recent work in monkeys with nigrostriatal damage shows that striatal α6* (and also α4*) nAChR function is at normal levels despite 50% receptor declines (McCallum et al., 2005a,b). These compensatory changes in function in the presence of significant nAChR losses suggest that subtype-selective agonists would be beneficial despite nigrostriatal damage. In addition, the use of nicotine or subtype-selective nicotinic receptor agonists may offer the advantage that released dopamine from the nerve terminal represents a more physiologic mode of stimulation of postsynaptic dopamine function than that which occurs in response to administration of L-dopa or dopamine agonists. There may be advantages in synchronizing postsynaptic dopamine receptor stimulation with presynaptically evoked action potentials that are not conserved with directly acting dopamine agonists. Indeed, previous work has shown that administration of nAChR agonists to monkeys in combination with L-dopa allowed for a reduction in L-dopa dosage without a loss in the antiparkinsonian efficacy of L-dopa (Schneider et al., 1998). The reduction in L-dopa dose may result in a decline in debilitating side effects, including dyskinesias and psychiatric disturbances, while maintaining the therapeutic response.

To date, studies investigating effects of nicotine administration for Parkinson’s disease therapy have been very limited and have yielded mixed results. Reductions in tremor and/or bradykinesia, as well as other improvements in motor performance, have been observed in some studies but not others (Ishikawa and Miyatake, 1993; Fagerstrom et al., 1994; Ebersbach et al., 1999; Kelton et al., 2000; Vieregge et al., 2001; Lemay et al., 2004). This inconsistency may relate to the small number of patients in the different studies as well as the short duration of nicotine treatment (a few weeks). The mode of nicotine administration has also been quite variable and includes i.v. infusion and/or use of the nicotine patch, gum, or lozenge. These dosing regimens are quite distinct, and the particular one selected may impact the behavioral response. For instance, chronic delivery with the nicotine patch will lead to steady-state nicotine levels that may result in greater receptor desensitization than intermittent regimens such as the gum or lozenge (Giniatullin et al., 2005; Wang and Sun, 2005). Further study to evaluate the potential for nicotine in the symptomatic treatment of Parkinson’s disease is critical.

**Neuroprotective Effect of Nicotine**

Another potential benefit of nAChR stimulation relates to neuroprotective effects against nigrostriatal damage. Nicotine or nicotinic agonists have been shown to attenuate a wide variety of toxic insults in culture models (O’Neill et al., 2002; Quik, 2004), including protection against MPTP-induced damage to nigral dopaminergic neurons (Jeyarasingam et al., 2002). Unexpectedly, protection by nicotine in this system seems to be mediated via non-α7 nAChRs in contrast to protection in most culture models in which α7 nAChRs seem to be involved (O’Neill et al., 2002; Quik, 2004). The effects of nicotine and nicotinic agonist have also been tested in rodent models of nigrostriatal damage; however, the results have proved rather variable, with some studies reporting a partial protection but others not (O’Neill et al., 2002; Quik, 2004). The reasons for these inconsistencies in vivo are unknown but may relate to the acute nature of the toxic insult and/or the short duration of nicotine treatment (Costa et al., 2001; Ryan et al., 2001). It may also be related to inherent differences between rodents and humans with respect to nicotine metabolism (which is much more rapid in rodents) and/or the nAChR subtypes present in striatum. Interestingly, in a recent chronic (~1 year) study in
Concluding Remarks

α6* nAChRs represent a subtype with a restricted localization in the CNS, including their presence on striatal dopaminergic terminals. They also exhibit a differential regulation in response to nicotine administration with declines in their number, in contrast to the well-known up-regulation of α4* nAChRs. The predominant α6* nAChR populations in both rodent and monkey striatum seem to be α6γ4β3δ and α6β2β3 complexes, although the subtypes and relative proportions of α3* and α6* nAChRs in human striatum await clarification. Since α6* nAChRs regulate dopamine release and are involved in motor behaviors, they may represent unique targets for the treatment of neurodegenerative disorders characterized by nigrostriatal dopaminergic damage, such as Parkinson’s disease. Selective α6* nAChR stimulation may afford symptomatic relief by stimulating dopamine release and/or reduce Parkinson’s disease progression through a neuroprotective action (O’Neill et al., 2002; Quik, 2004).

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References


Cui C, Booker TK, Allen RS, Grady SR, Whiteaker P, Marks MJ, McIntosh JM, Collins AC, and McIntosh JM (2002) Determination of amino acid residues that confer selectivity to α-conotoxin-MII[S4A;E11A;L15A] for the α6/β2β3 complexes, although the subtypes and relative proportions of α3* and α6* nAChRs in human striatum await clarification. Since α6* nAChRs regulate dopamine release and are involved in motor behaviors, they may represent unique targets for the treatment of neurodegenerative disorders characterized by nigrostriatal dopaminergic damage, such as Parkinson’s disease. Selective α6* nAChR stimulation may afford symptomatic relief by stimulating dopamine release and/or reduce Parkinson’s disease progression through a neuroprotective action (O’Neill et al., 2002; Quik, 2004).


