Striatal spine plasticity in Parkinson’s disease

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INTRODUCTION

Since 1891 when Cajal described dendritic spines as morphologically distinct neuronal elements (Ramon y Cajal, 1891), studies of spine development, morphogenesis and plasticity have been at the forefront of research in various laboratories using modern techniques at the electron microscopic level for three-dimensional (3D) reconstructions of individual spines (Harris and Kater, 1994; DeFelipe, 2002; Smith et al., 2009; Villalba et al., 2010), single- and two-photon microscopy used in conjunction with fluorescent molecular tools (Yuste and Bonhoeffer, 2004; Knott and Holtmaat, 2008) or neurocomputational methods (Zhang et al., 2010) to study dynamic changes in spine morphology related to pathological or physiological regulation of neuronal plasticity (Yuste and Bonhoeffer, 2001).

Despite a broad range of experimental evidence showing changes in the density or morphology of dendritic spines in a large number of neurological and psychiatric diseases, the exact contribution of spine changes to brain diseases pathophysiology remains poorly understood (Ingham et al., 1989, 1998; Harris and Kater, 1994; Fiala et al., 2002; Picconi et al., 2005; Stephens et al., 2005; Zaja-Milatovic et al., 2005; Deutch et al., 2007; Surmeier et al., 2007; Bourne and Harris, 2008; Smith and Villalba, 2008; Villalba et al., 2009, 2010).

In the striatum, the principal neuronal subtypes are the medium spiny neurons (MSNs), which represent 95% of all striatal neurons (Kemp and Powell, 1971; Chang et al., 1982). In rats, each MSN harbors approximately 5000 dendritic spines (Wickens et al., 2007). Each of these spines receives glutamatergic inputs from the cerebral cortex or specific thalamic nuclei (Kemp and Powell, 1971; Smith et al., 2004, 2009; Raju et al., 2006). Spines are also an important target of midbrain dopaminergic inputs that play a critical role in the regulation of cortical glutamatergic afferents (Smith and Bolam, 1990; Smith et al., 1994; Nicola et al., 2000). In both animal models of parkinsonism and Parkinson’s disease (PD) patients, MSNs lose as much 30–50% dendritic spines, which results in complex anatomical, neurochemical and electrophysiological changes of striatal glutamatergic transmission (Ingham et al., 1989; Stephens et al., 2005; Zaja-Milatovic et al., 2005; Smith and Villalba, 2008; Villalba et al., 2009).

The goal of this review is to provide an overall assessment of anatomical and functional evidence for spine loss in the striatum, and discuss the potential mechanisms involved in this pathophysiological phenomenon in parkinsonism. The readers are referred to other recent reviews for additional information (Deutchat et al., 2007; Smith and Villalba, 2008; Smith et al., 2009).

SPINE LOSS IN PARKINSON’S DISEASE AND PD MODELS

Over the past decades, it became clear that the progressive loss of striatal dopamine in PD patients and animal models of parkinsonism results in a significant loss of dendritic spines on MSNs of the dorsal striatum (Figure 1).

The first clear evidence for striatal spine loss came from studies showing that unilateral degeneration of the nigrostriatal dopaminergic system results in about 20% spine loss in the caudate-putamen complex of rats treated with 6-hydroxydopamine (6-OHDA) (Ingham et al., 1989). Since then, corresponding degrees of spine pruning have been demonstrated in postmortem striatal tissue of PD patients (Stephens et al., 2005; Zaja-Milatovic et al., 2005) and 1-methyl-4-phenyl-1,2,3,6-tetrahydropyridine (MPTP)-treated parkinsonian monkeys (Smith and Villalba, 2008; Villalba et al., 2009). In monkeys and humans, the extent of spine loss correlates with the relative degree of striatal dopamine denervation (Zaja-Milatovic et al., 2005; Smith and Villalba, 2008; Villalba et al., 2009). For instance, in MPTP-treated parkinsonian monkeys, MSNs in striatal regions most severely dopamine-depleted, like the postcommissural putamen (i.e., the sensorimotor striatum) lose as much as 50% spines, while spine loss in less affected striatal areas like the nucleus accumbens (i.e., the limbic striatum) ranges between 20% to 25% of total striatal spines (Villalba et al., 2009) (Figure 2).
Data obtained so far about this issue remain controversial. On one hand, observations gathered from reserpine-treated mice and 6-OHDA-treated rats suggested that D2-containing striatopallidal neurons, but not D1-positive striatonigral neurons, selectively lose spines following dopamine depletion (Day et al., 2006). These observations are at odds with a large number of studies in both human parkinsonians and animal models of parkinsonism showing a rather homogeneous loss of spines across large populations of Golgi-impregnated striatal MSNs (Ingham et al., 1989, 1998; Stephens et al., 2005; Zaja-Milatovic et al., 2005; Smith and Villalba, 2008; Villalba et al., 2009). Furthermore, recent data from rhesus monkeys chronically treated over many months with MPTP demonstrated a comparable loss of both D1-immunoreactive and D1-immunonegative spines in the DA-denervated putamen (Villalba et al., 2009), suggesting that spine pathogenesis affects both direct and indirect pathway striatofugal neurons in this animal model (Villalba et al., 2009). However, other monkey studies suggested a decrease in D2-positive spines accompanied with a
corresponding increase in D1-immunoreactive spines in the caudate nucleus of MPTP-treated cynomolgus monkeys (Scholz et al., 2008). These apparent discrepancies may be due to the use of different animal models, different regimens of neurotoxin administration, different quantitative methods to determine striatal spine loss and different striatal regions being examined.

DOES STRIATAL SPINE LOSS AFFECT PREFERENTIALLY CORTICAL- OVER THALAMIC-RECIPIENT TARGETS?
The striatum receives glutamatergic inputs from the cerebral cortex and the thalamus. Although cortical inputs target almost exclusively dendritic spines, a substantial component of the thalamostriatal system that originates from the caudal intralaminar nuclei, centered median and parafascicular nuclei, target preferentially dendritic shafts, whereas inputs from rostral intralaminar, relay and associative thalamic nuclei mainly innervate dendritic spines (Smith et al., 2004, 2009; Raju et al., 2008). Although these two glutamatergic inputs cannot be differentiated from each other solely based on structural features, they can be categorized as of cortical or thalamic origin based on their specific expression in vesicular glutamate transporter 1 (vGluT1) or vGluT2, respectively (Raju et al., 2006, 2008; Smith et al., 2009). Taking advantage of these specific markers, we recently reported a significant increase in the overall density of vGluT1-positive terminals, but no significant change in the prevalence of vGluT2-positive boutons in the striatum of MPTP-treated parkinsonian monkeys (Raju et al., 2008). These findings are supported by postmortem human data showing an increased vGluT1 protein expression in the striatum of parkinsonians (Kashani et al., 2007).

At first glance, these observations are paradoxical to the fact that striatal MSNs undergo significant spine loss in parkinsonism, and that the bulk of synaptic inputs to striatal spines originate from cortical terminals (Kemp and Powell, 1971; Smith and Bolam, 1990; Raju et al., 2008). However, they are consistent with a large number of electrophysiological and neurochemical studies that suggest an increased glutamatergic transmission at corticostriatal synapses and augmented neuronal excitability in the striatum of rodent models of parkinsonism (Gubellini et al., 2002; Mallet et al., 2006, but see Day et al., 2006). Recent evidence suggests that such increased striatal activity may also occur in MPTP-treated monkeys (Liang et al., 2008). Although there is no clear explanation for this apparent discrepancy between morphological and functional data related to the corticostriatal system in parkinsonism, there are various indications that the striatum undergoes complex compensatory changes in glutamate receptors expression (Betarbet et al., 2000) and synaptic architecture that may account for increased glutamatergic transmission in parkinsonian condition (see Smith et al., 2009, for a review).

ULTRASTRUCTURAL REORGANIZATION OF GLUTAMATERGIC CORTICOSTRIAL AND THALAMOSTRIAL SYNAPSES IN PARKINSONISM
Early rodent and human data, indeed, suggested morphological changes of asymmetric synapses consistent with increased synaptic activity in the dopamine-denervated striatum (Ingham et al., 1998; Meshul et al., 1999, 2000). These observations were recently supported an expanded by detailed 3D ultrastructural analysis (Figure 3).

Quantitative analysis of 3D-reconstructed axo-spinous cortico- and thalamostriatal analysis showed that the size of the postsynaptic density (PSD) area at both glutamatergic synapses is increased in the non-human primate model of PD, thereby suggesting that both thalamic and cortical inputs undergo plastic changes consistent with increased synaptic strength in parkinsonism (Smith et al., 2009; Villalba et al., 2010) (Figure 4).

Our data also revealed that the complexity and the total number of perforations at PSDs at corticostriatal and thalamostriatal glutamatergic synapses are increased in parkinsonism, a type of structural modification associated with increased synaptic efficacy and learning in the hippocampus (Nieto-Sampedro et al., 1982).

The exact mechanisms underlying these functional changes are not known, but it has been hypothesized that the compartmentalization of multiple transmission zones impedes the saturation of postsynaptic receptors and allow multiple transmitter
Despite clear evidence for major structural and functional plastic changes in glutamatergic transmission at axo-spinous synapses in the parkinsonian striatum, the mechanisms underlying this phenomenon remain poorly understood. However, there is some indication that calcium likely contributes to this plastic event (Segal et al., 2000; Sabatini et al., 2001; Oertner and Matus, 2005; Day et al., 2006; Deutch et al., 2007; Surmeier et al., 2007). Findings in support of a calcium-regulated mechanism were recently gathered from transgenic mice with EGFP-labeled D1 or D2 DA receptors. In EGFP-D2 mice, spine loss can be prevented by genetic deletion of Cav1.3α1 subunits or the pharmacological blockade of L-type Cav1.3 channels (Day et al., 2006). Knowing that D2 dopamine receptor signaling targets only the channels that contain the Cav1.3α1 subunit (Surmeier et al., 2007), these data suggest

**Figure 4** | Histograms comparing the morphometric measurements (spine volume, PSD area, terminal volume) of structural elements at corticostriatal and thalamostriatal glutamatergic synapses using the 3D reconstruction method of serial ultrathin sections collected from 30 axo-spinous synapses in normal and MPTP-treated monkeys. (A) In control monkeys, the spine volume (Vol. Spi), the PSD areas and the size of pre-synaptic terminals at corticostriatal synapses are significantly larger than those at thalamostriatal synapses (*P* < 0.001 for Vol. Sp. and PSD; *P* = 0.016 for terminal; t-test). (B) The same is true for MPTP-treated monkeys, except for the pre-synaptic terminals that do not display any significant size differences in this condition. (C,D) The spine volumes, the PSD areas and the volume of vGluT1- and vGluT2-containing terminals are significantly larger in MPTP-treated parkinsonian monkeys than in controls (*P* < 0.001; t-test).

**Potential Cellular, Molecular and Genetic Mechanisms for Striatal Spine Loss in Parkinson’s Disease**

Despite clear evidence for major structural and functional plastic changes in glutamatergic transmission at axo-spinous synapses in the parkinsonian striatum, the mechanisms underlying this phenomenon remain poorly understood. However, there is some indication that calcium likely contributes to this plastic event (Segal et al., 2000; Sabatini et al., 2001; Oertner and Matus, 2005; Day et al., 2006; Deutch et al., 2007; Surmeier et al., 2007). Findings in support of a calcium-regulated mechanism were recently gathered from transgenic mice with EGFP-labeled D1 or D2 DA receptors. In EGFP-D2 mice, spine loss can be prevented by genetic deletion of Cav1.3α1 subunits or the pharmacological blockade of L-type Cav1.3 channels (Day et al., 2006). Knowing that D2 dopamine receptor signaling targets only the channels that contain the Cav1.3α1 subunit (Surmeier et al., 2007), these data suggest
that a dysregulation of calcium concentrations, preferentially in D2-containing striatopallidal neurons, may ultimately lead to specific spine loss on indirect pathway neurons in the rodent striatum (Day et al., 2006; Deutch et al., 2007; Surmeier et al., 2007). Further support for the involvement of calcium in this process comes from observations showing that striatal areas poor in calbindin D-28k (CaB) (Francois et al., 1994), such as the postcommissural putamen (sensorimotor striatal territory), are those that display the most severe striatal spine loss in MPTP-treated monkeys (Villalba et al., 2009). Recent data from co-culture studies suggest that the pruning of glutamatergic synapses and spines in the striatum, dependent upon calcium entry through L-type calcium channels, involves the activation of the Ca$^{2+}$-dependent protein phosphatase, calcineurin and the up-regulation of the transcriptional activity of the myocyte enhancer factor 2 (MEF2). In turn, MEF2 up-regulation leads to increased expression of the Nurr77 and Arc genes linked to synaptic remodeling (Tian et al., 2010), thereby providing a signaling cascade through which striatal MSNs may undergo structural plasticity in parkinsonism (Tian et al., 2010).

It is noteworthy that MEF2 down-regulation is required for abnormal outgrowth of spines on striatal MSNs in cocaine-treated animals (Pulipparacharuvil et al., 2008). Together, these data indicate that MEF2 plays a critical role in regulating striatal spine plasticity in pathological conditions. Cholinergic signaling through M1 muscarinic receptors and Kir2 potassium channels is another essential trigger for the pruning of glutamatergic synapses in models of parkinsonism (Shen et al., 2009).

Despite the lack of direct evidence that any of the gene mutations characterized in PD underlie striatal spine loss, it is worth noting that PD-associated mutations that result in an increased kinase activity of Lrrk2 reduces neurite outgrowth in primary neuronal cultures and in the intact rat CNS, whereas LRRK2 deficiency leads to increased neurite length and branching (MacLeod et al., 2006). These findings, combined with evidence for strong Lrrk2 expression in striatal MSNs (Lee et al., 2010) and Lrrk2 enzymatic activity toward protein complexes involved in the formation of actin-enriched precursors of dendritic spines during neural development (Parisidou et al., 2009), suggest that LRRK2 mutation in PD may contribute to striatal spine pathology in these patients.
CONCLUDING REMARKS

Striatal spine loss is a cardinal pathological feature of PD. Despite clear evidence that nigrostriatal dopaminergic lesion induces significant striatal spine loss in various animal models of PD, there is no direct evidence that dopamine denervation is the causal factor of striatal spine pathology. In fact, recent in vitro and in vivo studies have indicated that striatal spine pruning of MSNs in response to dopamine denervation is significantly attenuated by cortical lesions (Neely et al., 2007; García et al., 2010), suggesting that glutamatergic cortical inputs are essential to mediate striatal spine loss in parkinsonism. Thus, whether striatal spine loss is the consequence of the lack of dopamine-mediated effects on corticostriatal glutamatergic transmission or primarily induced by dysfunction of the corticostriatal system remains to be established (Smith et al., 2009).

Another poorly understood aspect of this striatal pathology is its functional significance in PD symptomatology. Our recent observations that partially lesioned MPTP-treated monkeys with 30–40% spine loss in the sensorimotor striatum (i.e., the postcommisural putamen), do not display any significant parkinsonian symptoms suggest that the loss of spines in the motor striatum is not sufficient to elicit abnormal motor behaviors in parkinsonism (Smith et al., 2009; Villalba et al., 2009). Based on various findings from our laboratory and others showing the complex ultrastructural compensatory changes that affect remaining glutamatergic synapses in the dopamine-denervated striatum, we suggest that striatal compensatory changes that affect remaining glutamatergic synapses in the dopamine-denervated striatum, we suggest that striatal spine pathology provides further evidence that early striatal dysfunctions in dopaminergic and glutamatergic transmission are key elements of the complex pathophysiology of parkinsonism.

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