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Development/Plasticity/Repair

Ctip2 Controls the Differentiation of Medium Spiny Neurons and the Establishment of the Cellular Architecture of the Striatum

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Striatal medium spiny neurons (MSN) are critically involved in motor control, and their degeneration is a principal component of Huntington’s disease. We find that the transcription factor Ctip2 (also known as Bcl11b) is central to MSN differentiation and striatal development. Within the striatum, it is expressed by all MSN, although it is excluded from essentially all striatal interneurons. In the absence of Ctip2, MSN do not fully differentiate, as demonstrated by dramatically reduced expression of a large number of MSN markers, including DARPP-32, FOXP1, Chrm4, Reelin, MOR1 (μ-opioid receptor 1), glutamate receptor 1, and Plexin-D1. Furthermore, MSN fail to aggregate into patches, resulting in severely disrupted patch-matrix organization within the striatum. Finally, heterotopic cellular aggregates invade the Ctip2−/− striatum, suggesting a failure by MSN to repel these cells in the absence of Ctip2. This is associated with abnormal dopaminergic innervation of the mutant striatum and dramatic changes in gene expression, including dysregulation of molecules involved in cellular repulsion. Together, these data indicate that Ctip2 is a critical regulator of MSN differentiation, striatal patch development, and the establishment of the cellular architecture of the striatum.

Key words: Ctip2; striatum; medium spiny neurons; striasomes; striatal patches; secretagigin

Introduction

The striatum plays a central role in the coordination of movement, emotions, and cognition (Gerfen, 1992; Jain et al., 2001; Graybiel, 2005). GABAergic medium-sized spiny neurons (MSN), the output projection neurons of the striatum, account for the vast majority (~90–95%) of all striatal neurons (Kemp and Powell, 1971; Gerfen, 1992). The remaining 5–10% of striatal neurons are interneurons that can be subdivided into different functional classes based on neurotransmitter/neuropeptide profiles, and distinct morphological and electrophysiological properties (Kawaguchi, 1993; Kawaguchi et al., 1995; Tepper and Bolam, 2004). Clinically, MSN are an important population of projection neurons, because their degeneration is a critical component of Huntington’s disease; they are also an essential element of the circuitry that degenerates in Parkinson’s disease (Albin et al., 1989).

Transplantation and birth-dating studies have shown that MSN are born from Dlx1/2-positive progenitors located in the germinal zone of the developing lateral ganglionic eminence (LGE) (Deacon et al., 1994; Olsson et al., 1995, 1997; Wichterle et al., 2001). After migrating radially into the developing striatum, MSN segregate into two principal compartments: the patches (also known as striasomes) and the matrix that surrounds them (for review, see Gerfen, 1992). The first MSN to migrate into the developing striatum aggregate into the patches, whereas later-generated neurons form the matrix (van der Kooy and Fishell, 1987; Krushel et al., 1989, 1995; Song and Harlan, 1994). Striatal patches develop concomitantly with the arrival of dopaminergic afferents from the substantia nigra, which reach the striatum at embryonic day 14 (E14) and cluster at the patches by E19 (Moon Edley and Herkenham, 1984).

Several transcription factors have been shown to regulate the development of patch and/or matrix neurons by acting on the progenitors of MSN. For example, lack of Dlx1/2 causes arrested migration of matrix neurons within the subventricular zone (SVZ) (Anderson et al., 1997b), and Mash1 null-mutant mice exhibit a loss of neuronal progenitors, resulting in a reduction of defined neuronal populations in the basal ganglia (Casarosa et al., 1999). Other studies have looked at the effect of neurotrophin signaling on MSN development; these have found that TrkB re-
ceptor signaling via its ligand BDNF is implicated in both patch and matrix MSN maturation in vitro (Ivkovic and Ehrlich, 1999).

In contrast, less is known about the transcription factor codes that regulate MSN differentiation and patch-matrix development after the progenitor stage.

We demonstrated previously that the transcription factor COUP TF1-interacting protein 2 (Ctip2) plays critical roles during axonal extension and pathfinding by subcerebral projection neurons of the cerebral cortex (Arlotta et al., 2005). Here, we report that within the striatum Ctip2 is uniquely expressed by MSN, specifically labeling this critical neuronal population from early postmitotic stages. Loss of Ctip2 function results in a failure of MSN differentiation, disruption of the patch-matrix organization of MSN, and distinct changes in the expression of multiple genes, including novel molecular identifiers of the patch compartment. The defect in patch aggregation also results in abnormal dopaminergic innervation of the striatum. Finally, there is an alteration in the expression of molecules involved in cellular repulsion and the appearance of heterotopias within the mutant striatum, strongly suggesting that the loss of Ctip2 disrupts normal mechanisms of cellular repulsion during development.

Materials and Methods

Ctip2−/−, Chrm4GFP and Plexin-D1−/− mice. Ctip2−/− mice, generated by Wakabayashi et al. (2003), have a neomycin resistance gene inserted into exon 1 of the Ctip2 gene, blocking Ctip2 expression. Ctip2 mutant mice were maintained on a BALB/c background. Chrm4Gfp transgenic mice, which express enhanced green fluorescent protein (EGFP) under the control of the m4human muscarinic receptor (chrm4) promoter, were generated by the GENSAT Project using a bacterial artificial chromosome maintained in the C57BL/6 background (Gu et al., 2005), have a neomycin resistance gene inserted into exon 1 of the Plexin-D1 gene, blocking Plexin-D1 expression. For all embryonic experiments, the day of vaginal plug was designated E0.5. The day of birth was designated postnatal day 0 (P0). All mouse studies were approved by the Massachusetts General Hospital Institutional Animal Care and Use Committee and performed in accordance with institutional and federal guidelines.

Immunocytochemistry and in situ hybridization. Brains were fixed and stained using standard methods (Fricker-Gates et al., 2002). Briefly, brains were fixed by transcardial perfusion with PBS-heparin (10 U/ml) followed by 4% paraformaldehyde, and postfixed overnight at 4°C in 4% paraformaldehyde. Brains were sectioned coronally at 40 μm on a vibratome (Leica, Nussloch, Germany). Sections were blocked in 0.3% BSA (Sigma, St. Louis, MO), 8% goat or donkey serum, and 0.3% Triton X-100 (Sigma) for 1 h at room temperature, before incubation in primary antibody. Primary antibodies and dilutions used were rat anti-Ctip2 (1:500; a gift from Mark Leid, Oregon State University, Corvallis, OR); Senawong et al., 2003); rabbit anti-dopamine and cAMP-regulated phosphoprotein 32 kDa (DARPP-32), 1:250 (Millipore, Temecula, CA); mouse anti-FOXP1 (IC12; 1:10; a gift from Alison Banham, University of Oxford, Oxford, UK) (Banham et al., 2001); rabbit anti-FOXP1 (1:500, a gift from Daniel Simon, Harvard Medical School, Boston, MA) (Shi et al., 2004); goat anti-ChAT (1:100; Millipore); rabbit anti-somatostatin (1:100; Millipore); mouse anti-parvalbumin (1:2000; Millipore); anti-MAP2 (1:500; Sigma); anti-cleaved caspase 3 (1:750; NEB, Ipswich, MA); rat anti-BrdU (1:400; Accurate, Westbury, NY); rabbit anti-MOR1 (1:1000; Abcam, Cambridge, MA); rabbit anti-Secretagogin (1:3000; a gift from Ludwig Wagner, Medical University of Vienna, Vienna, Austria) (Gartner et al., 2001); mouse anti-Reelin (1:400; Millipore); rabbit anti-Glut1 (1:30; Millipore); mouse anti-TH (1:500; Millipore). Appropriate secondary antibodies were from the Invitrogen (Carlsbad, CA) Alexa series. Laser confocal analysis was performed using a Bio-Rad (Hercules, CA) Radiance 2100 confocal system attached to a Nikon (Tokyo, Japan) E800 microscope.

BrdU labeling. Timed pregnant females received a single intraperitoneal injection of bromodeoxyuridine (BrdU) (100 mg/kg) at E12.5. Embryos were collected at E19.5 or at P0. Brains were removed, fixed overnight at 4°C with 4% paraformaldehyde, and sectioned coronally at 40 μm thickness using a vibrating microtome (Leica). BrdU immunocytochemistry was performed as described previously (Magavi et al., 2000). For the detection of BrdU-positive nuclei, matching sections from three Ctip2−/− and three wild-type littersmates (every sixth section) were imaged, and two independent investigators, blinded to genotype, scored each section for the presence of BrdU-positive nuclei clustered in patches. There was high interobserver reliability, documenting a reduction in aggregation of BrdU-labeled MSN into patches within the mutant striatum. For the quantification of BrdU-positive cells born at E12.5, five matched sections were counterstained with FOXP1 (1 marker of MSN) to define the dorsoverentral and mediolateral limits of the striatum, including the subcallosal streak. Two independent investigators, blinded to genotype, counted the total number of first-generation BrdU-positive nuclei across the entire striatum and subcallosal streak in three Ctip2−/− and three wild-type littersmates.

TUNEL and Fluoro-Jade B staining. Terminal deoxynucleotidyl transferase-mediated biotinylated UTP nick end labeling (TUNEL) staining was performed using the DeadEnd Fluorometric TUNEL system (Promega, Madison, WI), following the instructions of the manufacturer. Fluoro-Jade B staining was performed according to Schmued and Hopkins (2000).

Affymetrix microarrays. Matched regions of striatum from wild-type and Ctip2−/− mice were obtained via 500-μm-diameter punch biopsies performed in the center of the developing striatum in acutely sectioned 300 μm coronal slices of the brain at P0. Sections were matched rostrocaudally between wild-type and null mutant tissue, and fiduciary landmarks were used to assure reproducible microdissection of comparable regions. RNA was extracted using the StrataPrep Total RNA Mini Kit (Stratagene, La Jolla, CA), and RNA quality was assayed using a bioanalyzer (Agilent Technologies, Palo Alto, CA). To ensure reproducibility and biological significance, microarrays were performed with RNA samples from three independent wild-type and four Ctip2−/− mice (biological replicates). Microarray data were normalized using two independent methods: the RMA function within Bioconductor (Irizarry et al., 2003) and the “error model” method within Rosetta Resolver (version 5.0; Rosetta BioSoftware, Seattle, WA). Statistical significance of gene expression differences between wild-type and knock-out was determined using statistical analysis of microarrays (SAM) (Tusher et al., 2001). Using a SAM D-score cutoff of >2 or less than −2, we selected the 153 most significant genes and further analyzed them to identify a smaller set of genes of potentially high biological relevance. All microarray data have been deposited in the Gene Expression Omnibus database at National Center for Biotechnology Information (accession number GSE9330).

In situ hybridization. In situ hybridization was performed using reported methods (Berger and Hediger, 2001). The probe for Plexin-D1 was as previously reported (Molyneaux et al., 2005), and the Nr1p/ probe was a gift from Antonello Mallamaci (S.I.S.S.A., Trieste, Italy). Template cDNA were amplified by RT-PCR using the primers listed in supplemental Table 1 (available at www.jneurosci.org as supplemental material) for the following genes: Basoonulin2, Eb1, Fidgetin, Kenp2, Meis2, Necln-3, Neto1, Neurotensin, Nefl, Nolz-1, Pep81, Semaphorin 3A, Semaphorin 3C, Semaphorin 3E, Semaphorin 3F, and Unc5d.

Results

Striatal Ctip2 expression is restricted to medium spiny neurons

Ctip2 is a transcription factor reported previously to be expressed in specific regions of the CNS, including the neocortex, the hippocampus, the olfactory bulb, and the striatum, from early embryonic stages of development (Leid et al., 2004; Arlotta et al., 2005). Within the striatum, Ctip2 is expressed in the vast majority of cells, suggesting that it might be expressed in MSN, which
CTIP2 is specifically expressed in medium spiny neurons. A–D, CTIP2 expression in MSN labeled with DARPP-32. A, Coronal section of adult striatum, showing colocalization of CTIP2 (red) with DARPP-32 labeled MSN (green). B, C, High-magnification image of DARPP-32 expression (B) and CTIP2-labeled nuclei (C) in the boxed area in A. D, Merged image of B and C, showing that all DARPP-32 labeled MSN express CTIP2. E–H, CTIP2 expression in MSN labeled with FOXP1. E, Coronal section of adult striatum, showing colocalization of CTIP2 (red) with FOXP1 labeled MSN (green). F, G, High-magnification image of FOXP1-labeled MSN (F) and CTIP2-labeled nuclei (G) in the boxed area in E. H, Merged image of F and G, showing that all FOXP1-labeled MSN express CTIP2. Fewer than 1% of CTIP2-labeled cells are FOXP1 negative (arrowhead). Arrows indicate examples of colocalization. Scale bars: A, 200 μm; B–D, F–H, 10 μm.

Absence of CTIP2 impairs the spatial organization of medium spiny neurons into striatal patches

To investigate whether CTIP2 plays a functional role in medium spiny neuron development, we examined the striatum of Ctip2−/− mice. Because Ctip2−/− mice die within the first 24 h after birth (Wakabayashi et al., 2003; Arlotta et al., 2005), we examined the mutant striatum at P0, when the bulk of MSN neurogenesis is complete and MSN have migrated into the striatum (Fig. 3A, B), and this expression is maintained at high levels into adulthood (Fig. 3C).

MSN are born in the lateral ganglionic eminence between E12 and P2 in rat (and corresponding developmental stages in mice) and then migrate radially away from the germinal zone into the developing striatum (Marchand and La joie, 1986; van der Kooy and Fishell, 1987). To define when during development MSN begin expressing CTIP2, we performed a developmental analysis of CTIP2 expression and colocalization with early neuronal and progenitor markers. In the LGE, CTIP2 is first detected at E12.5 (Arlotta et al., 2005) and continues to be strongly expressed throughout MSN neurogenesis from E13.5 into adulthood (Fig. 3A–C). Within the LGE, CTIP2 is not expressed in the ventricular or subventricular zones (Fig. 3A). Rather, at E13.5 and E17.5, it is expressed in the mantle zone of the developing striatum (Fig. 3A, B), suggesting that CTIP2 is first expressed in early postmitotic MSN and not in MSN progenitors. In agreement with these findings, CTIP2 expression colocalizes with immature doublecortin (Dcx)-positive migratory neurons at E13.5 (Fig. 3D–G) and is excluded from dividing progenitors in the VZ/SVZ, as identified by both phosphorylated histone 3 (PH3) and BrdU (Fig. 3H–K, L–O, respectively). CTIP2 expression levels increase in MSN as they migrate radially into the striatum (Fig. 3B), and this expression is maintained at high levels into adulthood (Fig. 3C).

Absence of CTIP2 impairs the spatial organization of medium spiny neurons into striatal patches

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tion neurons, to CTIP2 function in the striatum, or to a combination of the two.

Here, using Meis2 (Toresson et al., 2000a) and Nolz-1 (Chang et al., 2004) to label immature MSN within the developing LGE at E14.5 (supplemental Fig. 1A–D, available at www.jneurosci.org as supplemental material), and FOXP1 to label MSN within the mantle zone of the striatum at E15.5 and at P0 (Fig. 4A,B, supplemental Fig. 1E,F, available at www.jneurosci.org as supplemental material), we find that loss of Ctip2 does not affect MSN birth and migration into the striatum. However, the differentiation of these neurons is impaired, as reflected by a decrease in FOXP1 expression as early as E15.5 and a disorganization in striatal compartments. Moreover, Chrm4, a marker of the striatonigral subset of MSN (Ince et al., 1997), is virtually absent from the striatum of the null-mutant at P0, as measured by the absence of GFP reporter gene expression from the Chrm4 locus in transgenic mice (Fig. 4C,D). These data indicate that in the absence of Ctip2 MSN are specified from progenitors and migrate into the mantle zone, but differentiate abnormally.

To determine whether lack of Ctip2 function is associated with abnormal organization of different striatal cellular compartments, we labeled P0 striatum from Ctip2<sup>-/-</sup> and wild-type littermates for DARPP-32, Reelin, µ-opioid receptor 1 (MOR1), glutamate receptor 1 (GluR1), and microtubule-associated protein 2 (MAP2). Although patch-matrix segregation is not yet complete at P0, developing patches can be detected by these markers just before birth (Moon Edley and Herkenham, 1984; Foster et al., 1987; Snyder-Keller and Costantini, 1996; Nishikawa et al., 1999).

Staining for DARPP-32, a relatively late marker of MSN differentiation and patch organization, reveals striking differences between the wild-type and Ctip2<sup>-/-</sup> striatum. In the wild-type P0 striatum, DARPP-32 is expressed primarily in earlier born MSN that form the distinctive patches (Fig. 4E,F). In contrast, in the Ctip2<sup>-/-</sup> mutant, only occasional small clusters of neurons express DARPP-32 at extremely low levels; these rare neurons are usually located near the subcallosal streak of the Ctip2<sup>-/-</sup> striatum (Fig. 4F, arrowhead). Other than these rare neurons, the Ctip2<sup>-/-</sup> striatum is almost completely devoid of DARPP-32 expression (Fig. 4F,F'), indicating that Ctip2 might directly or indirectly regulate DARPP-32 expression in MSN.

Labeling of the Ctip2<sup>-/-</sup> striatum by Reelin, MOR1, and GluR1 (all markers of MSN of the patch compartment) (Fig. 4H,J,L) reveals absence of the distinct patches that are identified in wild-type striatum (Fig. 4G,I,K). Similarly, MAP2 expression is much more homogeneous in Ctip2 null mutant striatum than in wild-type striatum (Fig. 4M,M'), usually with only one or two large areas of dense staining in the subcallosal streak (Fig. 4N,N'). These data indicate that striatal patches do not develop normally in the absence of Ctip2 function.

Interestingly, MOR1 and GluR1 labeling reveal large, abnormal cellular aggregates in mutant striatum (Fig. 4J,L, arrowhead). The absence of DARPP-32 expression in these large cellular aggregates, which are quite different in shape and size from striatal patches in the wild-type, led us to investigate whether they are composed of patch neurons; we find that they are not. BrdU injection at E12.5, during peak production of patch neurons, allowed us to distinguish patch from matrix neurons, which are predominantly born at E17.5 (Marchand and Lajoie, 1986; van der Kooy and Fishell, 1987). At P0, BrdU clearly labels the developing patches in the wild-type striatum (Fig. 4O, arrows). In contrast, early born neurons in the Ctip2<sup>-/-</sup> striatum are substantially more homogeneous in distribution (Fig. 4P). These results strongly suggest that the large cellular aggregates detected by MOR1 and GluR1 labeling are not MSN patches, and confirm that, in the absence of Ctip2, striatal patches do not form properly. This is not attributable to early migrational arrest...

Figure 2. CTIP2 is not expressed in striatal interneurons. A, B, Somatostatin expression (A) and CTIP2-labeled nuclei (B) in the same area as C. Merged image of A and B showing that no somatostatin-expressing interneurons express CTIP2. D, E, ChAT expression (D) and CTIP2-labeled nuclei (E) in the same area as D. F, Merged image of D and E, showing that no ChAT-expressing interneurons express CTIP2. G, H, Calretinin expression (G) and CTIP2-labeled nuclei (H) in the same area as G. J, Merged image of G and H showing that no Calretinin-expressing interneurons express CTIP2. J, K, Parvalbumin expression (J) and CTIP2-labeled nuclei (K) in the same area as J. L, Merged image of J and K showing that no parvalbumin-expressing interneurons express CTIP2. Arrows indicate examples of cells that do not express CTIP2. Scale bars, 20 µm.
because we did not find MSN arrested in the SVZ of the Ctip2-/- mice. Additionally, there was no significant difference in the number of BrdU-positive cells born at E12.5 that migrated into the striatum between Ctip2-/- [67.6 ± 2.9 (SEM), n = 3]; wild-type, [71.5 ± 3.3 (SEM), n = 3] mice, further indicating that abnormalities in patch formation are not caused by the overt loss of MSN or abnormal migration of MSN into the striatum.

MSN neurons of the matrix also display abnormalities in differentiation. Like the patch neurons, they fail to express DARPP-32 and Chrm4 and exhibit decreased levels of FOXP1 expression. However, levels of the matrix-specific marker Ebf1 are not grossly different in the Ctip2-/- striatum, indicating that MSN of the matrix still maintain some of their typical differentiation markers in the absence of Ctip2 (Fig. 4Q,R).

To investigate whether decreased survival of MSN might account for the abnormalities in MSN differentiation, we examined Ctip2-/- striatum to determine whether there is an increase in cell death compared with wild-type striatum. Although we found that there is an increased level of cell death in the Ctip2-/- striatum (supplemental Fig. 2A–L, available at www.jneurosci.org as supplemental material), it is limited to the dorsal aspect of the mutant striatum and is not widespread enough to account for the broadly distributed phenotypic changes in MSN development that we observe. All together, these data demonstrate that Ctip2 is required for the development and maturation of MSN, and for the proper compartmentalization of MSN into patches and matrix.

Abnormal differentiation of MSN is associated with changes in gene expression in the striatum of Ctip2-/- mice

To investigate the molecular mechanisms that underlie Ctip2-dependent differentiation of MSN and that underlie the patch-matrix disorganization in the mutant striatum, we directly compared gene expression between wild-type and mutant striatum at P0. Because Ctip2-expressing MSN constitute 90–95% of the neurons within the striatum, we reasoned that we should be able to detect changes in medium spiny neuron gene expression in Ctip2 null mutants using microarrays. We microdissected small regions of striatum at matched locations in wild-type and Ctip2-/- mutant littersmates at P0 (see Materials and Methods), and used them in three independent microarray experiments. We selected the 153 most significant genes (see Materials and Methods) and further analyzed them to identify a smaller set of genes of potentially high biological relevance (supplemental Table 2, available at www.jneurosci.org as supplemental material).

To verify the microarray data and define the distribution of the identified genes in the striatum, we performed in situ hybridization or immunohistochemistry for 12 selected genes: Plexin-D1, Ngef, Nectin-3, Kcnip2, Pcp4L1, Neto1, Bascomelin 2, Fidgetin, Semaphorin 3e, Secretagogin, Unc5d, and Neurotensin. We find that all of these genes are either specifically downregulated (Plexin-D1, Ngef, Nectin-3 Kcnip2, Pcp4L1, Neto1), or upregulated (Bascomelin 2, Fidgetin, Semaphorin 3e, Secretagogin, Unc5d, Neurotensin), in the Ctip2-/- striatum, confirming and extending the microarray results (Fig. 5). Three genes, Plexin-D1, Ngef, and Nectin-3, appear to be broadly expressed in both the patch and matrix compartments of the wild-type, but nearly ab-
Failure of striatal patch aggregation is associated with abnormal dopaminergic innervation of the striatum in Ctip2<sup>−/−</sup> mice

We next investigated the connectivity of nigrostriatal afferents, which normally target the striatal patches, and observed clear abnormalities in the distribution and organization of these afferents at P0. We immunostained nigrostriatal afferent axons for tyrosine hydroxylase (TH) in wild-type and mutant striatum at E15.5 and P0. In P0 wild-type striatum, high levels of TH labeling colocalize with the striatal patches (Fig. 6B, arrows), whereas TH labeling is more diffuse and highly disorganized in the striatum of Ctip2<sup>−/−</sup> mice (Fig. 6F). Closer examination of the pattern and local distribution of TH<sup>+</sup> input in mutant striatum clearly highlights entire regions that are completely devoid of TH<sup>+</sup> input (Fig. 6F, arrowheads). These areas are highly reminiscent in size, location, and distribution of the ectopic cell aggregates that we identified by Secretagogin, Unc5d, and Neurotensin labeling (Fig. 5J–L). To investigate whether TH<sup>+</sup> axons are repelled from the same aggregates that express high levels of secretagogin, we colabeled wild-type and mutant striatum with TH and secretagogin, and, strikingly, found that TH-expressing nigrostriatal afferents do not invade secretagogin-positive clusters (Fig. 6F–H), strongly suggesting that these cellular...
aggregates are not composed of MSN. Because TH innervation of the striatum at E15.5 (i.e., before patch aggregation) is initially normal (Fig. 6A,E), we conclude that the lack of patch formation within the striatum is responsible for the observed abnormal distribution of nigrostriatal afferents at P0. Additionally, we find that Ctip2 is not expressed in nigrostriatal neurons of the substantia nigra pars compacta (supplemental Fig. 4A–D, available at www.jneurosci.org as supplemental material), the origin of the TH-positive axons that synapse onto the patches, demonstrating that the observed abnormalities in patch formation in the mutant are not secondary to abnormal nigrostriatal neurons.

**Ectopic non-MSN cellular aggregates populate the Ctip2−/− striatum**

The observation that TH+ afferents do not innervate the clusters of Secretagogin expressing cells suggested to us that the clusters might represent ectopic cells that migrated into the striatum of the Ctip2−/− mutant. These cell clusters are highly reminiscent of the dysmorphic GluR1-positive and MOR1-positive cellular aggregates detected in the mutant striatum (Fig. 4J,L). In fact, the large Secretagogin clusters colocalize with the GluR1-expressing aggregates, although they do not colocalize with MOR1-expressing aggregates (supplemental Fig. 3, available at www.jneurosci.org as supplemental material). Secretagogin-positive aggregates are also coincident with areas of reduced FOXP1 expression (Fig. 7A–C, arrows), further supporting the interpretation that they are not composed of MSN. Confocal analysis at the single-cell level within large Secretagogin-positive aggregates indicates that the majority of Secretagogin-positive cells do not express the MSN marker FOXP1 (Fig. 7D–F). Additionally, the secretagogin aggregates are largely not born at E12.5, the peak of patch MSN neurogenesis, as shown by lack of colocalization with BrdU labeling from an E12.5-born at E12.5, the peak of patch MSN neurogenesis, as shown by lack of colocalization with BrdU labeling from an E12.5 pulse (Fig. 7G–I). Together, these data indicate that the aggregates are not composed of medium spiny neurons and raise the possibility that the cells that constitute them might have ectopically migrated into the Ctip2−/− striatum. In further support of this hypothesis, we observed similar clusters of cells expressing Semaphorin 3E (Fig. 5I), Unc5d (Fig. 5K), Neurotensin (Fig. 5L), and Neuropilin 1 (Fig. 8F) within the mutant striatum.

We next examined the location of Secretagogin expressing cells during development in the wild-type and Ctip2−/− brain to elucidate the developmental and spatial origin of the heterotopic aggregates. Throughout development, Secretagogin expression is limited to just a few areas of the brain. Interestingly, at E15.5, when MSN are starting to form the striatum, there is a population of secretagognin expressing cells located just ventral to the developing striatum (Fig. 8A,B, arrows). At P0, secretagogin cells are located in the olfactory bulb, as well as ventral to the striatum, in both the wild-type and Ctip2−/− mutant mice (Fig. 8C,D, arrows), whereas only the mutant striatum contains secretagogin
cellular aggregates (Fig. 8D, arrowhead). These cellular aggregates are present as early as E17.5 (data not shown). Together, these data suggest that the population of cells ventral to the striatum might represent the source of secretagogin-expressing cells that later infiltrate the striatum in the absence of CTIP2.

In agreement with the presence of ectopic cellular aggregates in the mutant striatum, our microarray data identified multiple molecules known to mediate cellular repulsion that are differentially expressed within the Ctip2 mutant striatum, including Plexin-D1, Semaphorin 3E, and Neuropilin 1 (supplemental Table 2, available at www.jneurosci.org as supplemental material) (Marin et al., 2001; Gu et al., 2005; Watakabe et al., 2006). Although the mutant striatum has dramatically decreased levels of Plexin-D1 and possesses ectopic clusters of cells expressing its ligand, Semaphorin 3E, the loss of Plexin-D1 alone is not sufficient to recapitulate the phenotype seen in the absence of Ctip2 (supplemental Fig. 5, available at www.jneurosci.org as supplemental material). This is consistent with the current model of Semaphorin 3E acting solely as a secreted ligand. To investigate the role of Neuropilin 1, we examined its expression by in situ hybridization and found that it is expressed in ectopic clusters of cells within them mutant (Fig. 8F, arrows) that are not present in the wild-type (Fig. 8E). However, the levels of Semaphorin 3A and Semaphorin 3F, which are known to mediate repulsion of Neuropilin 1 cells migrating around the striatum (Marin et al., 2001; Tamamaki et al., 2003), were not changed in the mutant striatum. This indicates that abnormalities in the expression of other, yet unidentified, ligands are likely responsible for the presence of the ectopic cells.

Discussion

Here, we report that CTIP2, a transcription factor that we found previously to play critical lineage-specific roles in corticospinal motor neuron development in the neocortex (Arlotta et al., 2005), is specifically expressed by striatal medium spiny neurons and is required for the proper differentiation of this important projection neuron type. In the absence of Ctip2, MSN of both the patch and the matrix compartments develop abnormally, as indicted by a dramatic dysregulation of several known and novel striatal genes in Ctip2−/− striatum. MSN are born in correct number and migrate into the striatum but they fail to aggregate into patches, and afferent dopaminergic innervation, normally targeted to the patches in wild-type striatum, is highly disorganized and entirely repelled from distinct areas within the mutant striatum. The areas of TH depletion coincide with aggregates of ectopic cells that appear to invade the striatum in the absence of Ctip2, and are identified by GluR1 and Secretagogin labeling. These cellular aggregates are not striatal patches: they are much larger and morphologically distinct from developing P0 wild-type patches; they are largely devoid of patch markers (e.g., DARPP-32 and Reelin); they repel (or are repelled by) afferent dopaminergic input from the substantia nigra; and they are not composed of cells born at E12.5, the period of peak neurogenesis of patch MSN. Together, these data indicate that CTIP2 plays an essential role in the development of MSN in the striatum, critically controlling patch-matrix compartmentalization of MSN in vivo.

CTIP2-mediated regulation of medium spiny neuron development

CTIP2 expression is first detected at the interface between the SVZ and the mantle zone in Doublecortin-expressing immature neurons, indicating that CTIP2 is expressed in early postmitotic MSN. Therefore, the observed abnormalities in MSN differentiation in Ctip2−/− mice are very likely caused by defects in postmitotic maturation and connectivity of MSN, rather than to an earlier fate specification defect in MSN progenitors. This neuron type-specific and temporal expression of CTIP2 in the striatum

Figure 6. Abnormal nigrostriatal innervation of the Ctip2−/− striatum. A, E, Coronal sections of wild-type (A) and mutant (E) developing striatum at E15.5 stained with TH, showing comparable distribution of TH innervation at this age, before aggregation of the patches occurs. B–D, F–H, Coronal sections of wild-type (B–D) and Ctip2−/− (F–H) striatum at P0 stained with TH and secretagogin. B, TH staining of wild-type striatum reveals distinct colocalization with developing striatal patches (arrows). F, In contrast, TH staining is diffuse and disorganized in Ctip2−/− striatum, showing no colocalization with patches, and delineating distinct areas of TH depletion (arrowheads). C, Secretagogin staining reveals no cells are labeled in wild-type striatum. D, Merged image of B and C. G, In contrast, large aggregates of secretagogin positive cells are present in Ctip2−/− striatum; these aggregates exclude TH innervation (H). Scale bars: A–H, 50 μm.

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shows remarkable parallels to that in the neocortex, where CTIP2 is expressed at high levels in postmitotic neurons in the cortical plate and not in progenitors in the VZ/SVZ (Arlotta et al., 2005). Within the cortex, CTIP2 exhibits lineage-restricted high-level expression in corticospinal and cortico-brainstem projection neurons. Similarly, within the striatum, CTIP2 is restricted to MSN (the striatal output projection neurons), together suggesting that CTIP2 controls lineage-restricted pathways of gene regulation in specific projection neuron populations of the brain.

Within the pathways of medium spiny neuron specification and differentiation, Ctip2 likely acts downstream of genes such as Gsh2, Dlx1/2, Mash1, and Islet1, which have been shown previously to play important roles in the specification of the ventral telencephalic identity of progenitors in the VZ and/or SVZ (Anderson et al., 1997a; Casarosa et al., 1999; Yun et al., 2001; Stenman et al., 2003). Whereas Ctip2 expression is first detected in migrating MSN, Gsh2, Dlx1/2, Mash1, and Islet1 are expressed much earlier in the progenitors that give rise to MSN. Similar to Ctip2−/− mice, Gsh2−/− mice also show a decrease in DARPP-32 expression and abnormal patch formation. However, this phenotype is secondary to changes in the progenitor population in the VZ of the Gsh2−/− LGE (Corbin et al., 2000; Toresson et al., 2000b; Toresson and Campbell, 2001). In the future, it will be interesting to investigate directly if and how CTIP2 interacts with each of these other transcription factors in controlling the development of medium spiny neurons.

Interestingly, CTIP2 and the closely related transcription factor CTIP1 can both interact directly with members of the chicken ovalbumin upstream promoter transcription factor (COUP-TF) family of transcription factors (Avram et al., 2000), and they have both been reported to act as transcriptional repressors in vitro. However, COUP-TF1 and CTIP2 patterns of gene expression are not completely overlapping in the brain, suggesting the possibility that CTIP2 may confer lineage-specificity to COUP-TF1-mediated gene regulation. Like Ctip2, Ctip1 is expressed at high levels in the striatum during development (Leid et al., 2004) in a pattern consistent with expression in MSN. Because the Ctip1 and Ctip2 genes share a high degree of homology (Avram et al., 2000, 2002), the presence of Ctip1 might partially compensate for the loss of Ctip2 in Ctip2−/− mutants, resulting in a more mild phenotype. Consistent with this hypothesis, we found that Ctip1 exhibited increased expression in the Ctip2 mutant by microarray (supplemental Table 2, available at www.jneurosci.org as supplemental material).

Nevertheless, in the absence of Ctip2 alone, there are drastic changes in the expression of many genes, several of which appear to be novel identifiers of the patch and/or matrix compartments at P0. The almost complete absence of DARPP-32 expression in the Ctip2 mutants raises the interesting possibility that Ctip2 activates the DARPP-32 gene via binding directly or indirectly (e.g., via COUP-TF1) to the DARPP-32 promoter. Supporting this hypothesis, we identified a CTIP2 consensus binding site that is highly conserved across species (Molyneaux et al., 2000, 2002) at P0. The almost complete absence of DARPP-32 expression in the Ctip2 mutants raises the interesting possibility that Ctip2 activates the DARPP-32 gene via binding directly or indirectly (e.g., via COUP-TF1) to the DARPP-32 promoter. Supporting this hypothesis, we identified a CTIP2 consensus binding site that is highly conserved across species (Molyneaux et al., unpublished observations). It will be interesting to investigate the ability of CTIP2 and COUP-TF1 to regulate the expression of DARPP-32 via binding to these sites.

**Ectopic cellular aggregates in the striatum of Ctip2−/− mice**

Although the Ctip2 mutant lacks striatal patches, the mutant striatum does contain large, disorganized aggregates of cells expressing Secretagogin, Neurotensin, or Unc5D. The origin of these cells is unclear. One possibility is that they could be a subpopulation of medium spiny neurons that are exhibiting extremely abnormal
patterns of gene expression and aggregation in the absence of Ctip2. However, given their expression of Secretagogin, the largely absent FOXP1 expression, the fact that they are not born during the peak period of patch neurogenesis, and that they appear to repel TH-positive afferents, these aggregates likely consist of cells that have migrated aberrantly into the striatum.

During normal development, striatal neurons repel streams of migrating cells destined for distant locations such as the cortex and olfactory bulb (Marin et al., 2001; Wichterle et al., 2001). Semaphorin 3A and Semaphorin 3F are two ligands expressed in the striatum that are known to mediate repulsion of migrating interneurons destined for the neocortex via interactions with Neuropilin 1 expressed on the surface of the migrating neurons (Marin et al., 2001). Although we found that Neuropilin 1 is expressed at elevated levels within clusters of ectopic cells found in the mutant striatum, we did not detect any differences in striatal expression of Semaphorin 3A and Semaphorin 3F at E14.5. Therefore, additional, yet unidentified diffusible ligands that are dysregulated in the striatum of the mutant must play a central role. Future experiments will seek to clarify the origin of the cellular aggregates and identify the extent of molecules expressed by MSN that mediate cellular repulsion, as well as to further define the mechanisms that mediate Ctip2 control over the development of the medium spiny neuron lineage in vivo.

References


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