L-DOPA-induced Dyskinesia is Associated with Regional Increase of Striatal Dynorphin Peptides as Elucidated by Imaging Mass Spectrometry*

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Opioid peptides are involved in various pathophysiological processes, including algesia, epilepsy, and drug dependence. A strong association between L-DOPA-induced dyskinesia (LID) and elevated prodynorphin mRNA levels has been established in both patients and in animal models of Parkinson’s disease, but to date the endogenous prodynorphin peptide products have not been determined. Here, matrix-assisted laser desorption ionization (MALDI) imaging mass spectrometry (IMS) was used for characterization, localization, and relative quantification of striatal neuropeptides in a rat model of LID in Parkinson’s disease. MALDI IMS has the unique advantage of high sensitivity and high molecular specificity, allowing comprehensive detection of multiple molecular species in a single tissue section. Indeed, several dynorphins and enkephalins could be detected in the present study, including dynorphin A(1–8), dynorphin B, α-neoendorphin, MetEnkRF, MetEnkRGL, PEnk (198–209, 219–229). IMS analysis revealed elevated levels of dynorphin B, α-neoendorphin, substance P, and PEnk (220–229) in the dorsolateral striatum of high-dyskinetic animals compared with low-dyskinetic and lesion-only control rats. Furthermore, the peak-intensities of the prodynorphin-derived peptides, dynorphin B and α-neoendorphin, were strongly and positively correlated with LID severity. Interestingly, these LID associated dynorphin peptides are not those with high affinity to opioid receptors, but are known to bind and activate also μ- and δ-opioid receptors. In addition, the peak intensities of a novel endogenous metabolite of α-neoendorphin lacking the N-terminal tyrosine correlated positively with dyskinesia severity. MALDI IMS of striatal sections from Pdyn knockout mice verified the identity of fully processed dynorphin peptides and the presence of endogenous des-tyrosine α-neoendorphin. Des-tyrosine dynorphins display reduced opioid receptor binding and this points to possible novel nonopioid receptor mediated changes in the striatum of dyskinetic rats. Because des-tyrosine dynorphins can only be detected by mass spectrometry, as no antibodies are available, these findings highlight the importance of MALDI IMS analysis for the study of molecular dynamics in neurological diseases. Molecular & Cellular Proteomics 10: 10.1074/mcp.M111.009308, 1–14, 2011.

The dopamine precursor L-3,4-dihydroxy-phenylalanine (L-DOPA)1 is still the most effective drug for symptomatic treatment of Parkinson’s disease (PD). However L-DOPA pharmacotherapy is accompanied by debilitating motor complications including L-DOPA-induced dyskinesia (LID). Evidence point to a fundamental disturbance of the basal ganglia function induced by the loss of dopamine (DA) and that leads to the facilitation of dyskinogenesis in PD (1).

L-DOPA-induced dyskinesia in patients with PD has been linked to elevated levels of preproenkephalin (PPE or PPE-A) and prodynorphin (PDyn or PPE-B) mRNA in the striatum (2–4). Similarly increased striatal levels of PPE mRNA, but even more pronounced PDyn mRNA levels have been reported in DA-denervated animal models of LID, including primates, monkeys, and rodents (5–10).

To our knowledge no study has assessed changes in neuroactive opioid levels in relation to LID in PD, despite numer-

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1 The abbreviations used are: L-DOPA, L-3,4-dihydroxy-phenylalanine; DHB, 2,5-dihydroxybenzoic acid; 6-OHDA, 6-hydroxydopamine; AIM, Abnormal involuntary movements; aNeo, Alpha-neoendorphin; CPs, Caudate putamen; DA, Dopamine; DynB, Dynorphin B; IMS, Imaging mass spectrometry; KOPr, MOPr, DOPr, kappa -, mu -, delta-opioid receptor; LID, L-DOPA-induced dyskinesia; LC-ESI FTICR MS, Liquid chromatography-electrospray Fourier transform mass spectrometry; MALDI, Matrix-assisted laser desorption/ionization; PD, Parkinson’s disease; PPE, Preproenkephalin; PDyn, Prodynorphin; PEnk, Proenkephalin; RIA, Radioimmunoassay; ROI, Regions of interest; SAM, Statistical analysis of microarray data; SP, Substance P.
ous studies on opioid precursor mRNA (11). In fact, little is known about which distinct opioid precursor-derived peptide products are involved in pathophysiologic mechanisms underlying LID. PPE mRNA can be processed into e.g. enkephalin, leu-enkephalin (Leu-Enk), met-enkephalin (Met-Enk), and enkephalin-containing peptide E and peptide F, whereas PDyn mRNA can be processed into several different dynorphins; including dynorphin A (DynA), dynorphin B (DynB), α/β-neoendorphin (α/βNeo), and Leu-Enk (12, 13).

So far only immunohistochemistry and radioimmunoassay (RIA) have been used to study changes in levels of specific endogenous opioid peptides in the human parkinsonian brain. In the post mortem PD striatum, Met-Enk and Leu-Enk peptide levels were decreased and DynA (1–8; 1–13 and/or 1–17) peptide levels remained unchanged, however the presence or severity of LID was not reported in these early studies (14–16). In addition, clinical and preclinical studies of the effects of opioid antagonists on LID have often displayed conflicting results (11). For example, nonselective opiate antagonists have been associated with both ailing and worsening of LID in PD patients and animal models (10, 17–20).

In the rat model of LID and PD, the expression of PDyn mRNA correlates highly with the level of FosB-related transcription factors in medium-sized spiny neurons of the dorsolateral striatum of animals displaying axial, limb and orolinguo-dyskinesia (21). In addition, prodynorphin mRNA and FosB-related protein levels were both elevated in the medial striatum in animals exhibiting rotational locomotive activity (21). Because of this distinct regional protein and peptide expression patterns related to behavior it is important to study molecular correlates of LID using advanced imaging techniques that offer high molecular specificity. In the present study we investigated region-specific expression of striatal neuropeptides in the rat model of LID and PD using matrix-assisted laser desorption and ionization (MALDI) imaging mass spectrometry (IMS; Fig. 1A). MALDI-IMS is an emerging technique of great potential for spatial profiling of molecular species in biological tissue samples (22, 23). Mass spectroscopic molecular imaging is advantageous in that it allows for the detection of many different analytes simultaneously in native tissue sections. In order to detect and image neuropeptides, 2,5-dihydroxybenzoic acid was used as a MALDI matrix and the sections were analyzed on a MALDI-TOF operating in reflector mode (24, 25). Several groups have analyzed single brain sections to obtain information of distribution patterns of endogenous neuropeptides or to describe technical improvements (26–31). However to our knowledge, this is the first report of a MALDI IMS-based statistical interrogation of pathophysiological changes in endogenous neuropeptide levels in the mammalian brain.

**EXPERIMENTAL PROCEDURES**

*Reagents—*Acetonitrile, methanol, acetic acid, ammonium acetate, ammonium bicarbonate, ammonium-dihydrogen-phosphate (NH₄H₂PO₄), formic acid and ethanol was of pro-analysis grade and purchased from Merck (Darmstadt, Germany). Trifluoroacetic acid was obtained from Sigma Aldrich (St. Louis, MO). Water was purified with a Milli-Q (Millipore, Bedford, MA) purification system. 2,5-dihydroxybenzoic acid (DHB), peptide and protein calibration standards were purchased from Bruker Daltonics (Bremen, Germany).

**Pdyn Knockout Mice—**Pdyn+/− mice were originally obtained by targeted deletion of the coding exons of the prodynorphin gene and bred into a 129Sv/Ev-Tac background as described (32). Animals were housed in groups of up to four per cage with food and water ad libitum in a room with a 12:12 h light:dark cycle. DNA from each animal was extracted for subsequent genotyping to confirm the identity of the Pdyn locus as described (32). Brain tissues were isolated from two male and one female Pdyn knockout mice after overexposure to halothane and cervical dislocation, and frozen in liquid nitrogen.

**Experimental Model of Parkinson’s Disease**

**Unilateral Lesion Surgery—**Female Sprague-Dawley rats (B&K, Sol-lentuna, Sweden), weighing 210 to 250 g at the time of surgery were housed four to a cage in a room with a 12 h light/dark cycle with food and water ad libitum. The experiments were approved by the Uppsala animal ethical committee and followed the guidelines of Swedish legislation on animal experimentation (Animal Welfare Act SFS1998: 56) and European Union legislation (Convention ETS123 and Directive 86/609/EEC). Rats anesthetized with isoflurane (2.5%, Apoteksbolaget AB, Stockholm, Sweden) received stereotaxic injections of 6-hydroxydopamine hydrochloride (6-OHDA-HCl) to the right ascending DA fiber bundle, as described previously (5). Briefly, 6-OHDA-HCl (Sigma Aldrich) was dissolved in 0.02% ascorbate acid in saline at a concentration of 3.6 μg/μl and injected at the following coordinates in millimeters relative to the bregma and the dural surface (33): (1) A, -4.4; L, 1.2; V, 7.8; tooth bar at –2.3 (7.5 μg deposit); (2) A, -4.0; L, 0.75; V, 8.0; tooth bar at +3.4 (6 μg deposit). 6-OHDA infusions were performed at 1 μl/min using a 10 μl Hamilton syringe. For post-operative analyses the rats were given Rimadyl (5 mg/kg, s.c., Apoteksbolaget AB).

**l-DOPA Treatment and Behavioral Analysis—**Forelimb use asymmetry was assessed using the cylinder test screening at 3 weeks post-6-OHDA lesion (34). Briefly, rats were placed in a glass-cylinder in a new environment and their forelimb touches (summing up to 20) were counted as they were rearing to explore the new environment. Only rats that used their contralateral forelimb less than 30% of the time were included in this study, corresponding to approximately >70% striatal DA depletion (35). l-DOPA treatment and recording of dyskinesia started the day after the limb-asymmetry test. l-DOPA and the peripheral DOPA-decarboxylase inhibitor, benserazide-HCl, were purchased from Sigma. At 3 weeks post lesion, rats started to receive single daily intraperitoneal injections of 8 mg/kg l-DOPA plus 15 mg/kg benserazide, or physiological saline (“lesion-only” controls). l-DOPA-induced abnormal involuntary movements (AIMs) were recorded every other day according to Cenci et al. (1998) (5). Briefly, rats were observed individually every 20th minute (1-min monitoring periods) during the 3 h, which followed a daily l-DOPA dose. Repetitive movements which affected the side of the body contralateral to the lesion, and could not be ascribed to any normal behavioral pattern, were classified into four subtypes: locomotive AIMs, i.e. increased locomotion with contralateral side bias; axial dystonia, i.e. contralateral twisted posturing of the neck and upper body; orolinguo AIMs, i.e. stereotyped jaw movements and contralateral tongue protrusion; and forelimb dyskinesia, i.e. repetitive jerks of the contralateral forelimb, sometimes combined with grabbing movements of the paw. Each rat was scored on a severity scale from 0 to 4 on each of these four subtypes; the theoretical maximum score that could be reached by a rat in one session was thus 144 (maximum score per
Dynorphin Peptide Alterations in L-DOPA-induced Dyskinesia

Peptide Extraction from Tissue Homogenates—Striatal opioid peptides were characterized using a modified protocol based on strong cation exchange prefracionation as described previously (39, 40). Briefly, frozen rat brain was mounted on a cryostat chuck at −20 °C, the cortex and corpus callosum removed and the nucleus accumbens (NAc) was separated from the caudate putamen by a thin cut from the most ventral point of the lateral ventricle to the most ventral point of the external capsule. Tissue sections from the CPu and NAc (20 μm, n = 50 and 50, respectively) were thaw-mounted on separate super-frost glass slides (Thermo Scientific, Waltham, MA). Off tissue extraction was performed by repeated addition and collection of 300 μl-crotiler 5% acetonitrile, 0.1% trifluoroacetic acid. The combined extracts were centrifuged at 5000 × g for 10 min. The supernatant was applied to small ion exchange columns (SP C25 Sephadex, GE Healthcare, Uppsala, Sweden), and eluted stepwise with buffers containing pyridine in 0.1% formic acid (0, 30, 70, and 100% pyridine). The fractions were dried down under reduced pressure using a speedvac system (Thermo Savant, Waltham, MA) and stored at 4 °C. Prior to further analysis the individual fractions were reconstituted in 50 μl 1% HAc and analyzed by means of nano-LC-ESI FTICR MS. LC-ESI FTICR MS—LC-ESI FTICR MS was performed on an Agilent 1100 nanoflow system (Agilent Technologies, Santa Clara, CA) hyphenated to a LTO-FT 7.0 T (Thermo Scientific). A volume of 5 μl from the reconstituted SCX fraction was injected automatically and loaded onto a self prepared C18 PicoFrit column (75 μm ID/15 μm tip ID, NewObjective, Woburn, MA) packed directly inside the electrospray needle tip using specially designed nanospray emitter tips. A water/formic acid/acetonitrile solvent system was used where solvent A was 0.1% formic acid and solvent B was 100% acetonitrile, 0.1% formic acid. Gradient elution was performed from 0% B for 10 min, the from 0% B to 50% B for 100 min, then from 50% B to 90% B for 5 min, then 90%B for 5 min and finally from 90% B back to 0% B for 5 min. Peptide elution was followed by ESI FTICR MS and tandem mass spectrometry (MS/MS) for peptide sequencing controlled by the Xcalibur software (version 2.0 SR2, Thermo Scientific). Fullscan spectra were acquired at high resolution (FWHM = 100000) using the FT analyzer. Data dependant acquisition was applied for MS/MS precursor selection, where the five most intense mass peaks were subjected to subsequent isolation and collision-induced fragmentation in the ion trap. Acquired raw data were exported to an mgf file using an in-house written script (C++).

Peptide Sequence Identification—The annotated fragment spectra were subjected to database search using, the Mascot search engine (version 2.2, Matrix Science, London, UK) (1–43). Mascot searches were performed against two databases containing sequences of known rat neuropeptides (SwePep peptides, 245 peptide entries, www.swepep.org) and neuropeptide precursor proteins (Swepep precursor, 123 protein entries) using the following specifications: mass tolerance (MS: ±20 ppm, MS/MS: ±1.2 Da) enzyme (none), fixed modifications (none), variable modifications (deamination, C-term. amidation, oxidation of Met), max. precursor charge (4+) and instrument (ESI-TRAP). Peptide matches with a score above the confidence threshold (p < 0.05) were considered to be a significant
hit. The false positive identification rate (FPR) was estimated by searching the data against a decoy database, where the FPR threshold was set to $1\%$.

**RESULTS**

**Chronic Intermittent L-DOPA-Treatment Results in Both High- and Low-dyskinetic Animals—**Dyskinesia ratings were conducted every other day during 15 days of L-DOPA treatment with once daily injections of a relative low dose L-DOPA (8 mg/kg L-DOPA and 15 mg/kg benserazide; see supplemental Fig. S1 for experimental workflow). Severe dyskinesia was observed in six animals (high dyskinetic, HD group) and 10 animals remained low dyskinetic until the end of the treatment period (LD group). The HD group displayed a 10-fold higher dyskinesia score compared with low dyskinetic (LD) animals ($p < 0.01$ HD versus LD group) (Fig. 1B). Only three animals displayed low to moderate levels of spontaneous locomotive and rotational activity in combination with axial dystonia. The extent of 6-OHDA-lesion was equal in all groups, including the lesion control group (LC, $n = 4$), with less than 10% of the number of TH-immunopositive cells remaining on the lesion side compared with the intact control substantia nigra (mean ± S.E.; LC group 7.75% ± 1.65, LD group 8.97% ± 2.23, and HD group 10.5% ± 2.93). The DA-denervated side of the striatum displayed a typical loss of DAergic innervation, as visualized by TH-immunochemistry (Fig. 1C).

**MALDI Imaging MS and Identification of Neuropeptides—**MALDI IMS experiments were performed in triplicates resulting in three data sets each comprising striatal sections from 18 animals (sections of two LD animals displayed severe freeze artifacts, generated low signal-to-noise spectra and were excluded from further analysis). The MS analysis revealed more than 1000 peaks, with the equivalent of about three peaks/peptide, resulting in the detection of 350 monoisotopic peptide peaks in mass spectra acquired from the striatal ROI, comprising the dorsolateral (DL) and dorsomedial (DM) regions of interest (ROI) for MS analysis. * $p < 0.01$. Scale bar 2.5 mm.

Fig. 1. **MALDI imaging mass spectrometry.** A, Experimental workflow: Sections of frozen rat brains are thaw-mounted onto MALDI compatible glass slides. MALDI matrix solution is applied as discrete spots in a quadratic pattern and mass spectra from individual matrix deposits are acquired by means of MALDI TOF MS. The intensity distribution of individual peaks is visualized using user-defined colors, here in green SP; in violet PENk 220–229; in red PEP-19 fragment; in blue MBP fragment. B, Behavioral analysis: High dyskinetic (HD) animals accumulated a 10-fold higher dyskinesia score than low dyskinetic (LD) animals. C, Unilateral DA denervation: Unilateral 6-OHDA-lesion model of experimental PD results in selective dopamine-denervation of striatum, revealed by a loss of tyrosine hydroxylase immunoreactivity. D, Regional analysis: Several markers were visualized to delineate anatomical features, including myelin basic protein (m/z 2028; blue) that is predominantly abundant in the corpus callosum, and a PEP-19 fragment (m/z 1755; red) that is exclusively observed in the striatum. The striatum was divided into a dorsomedial (DM) and a dorsolateral (DL) regions of interest (ROI) for MS analysis. * $p < 0.01$. Scale bar 2.5 mm.
Dynorphin Peptide Alterations in L-DOPA-induced Dyskinesia

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\(a\) Peptide database entry, sequence and accession number were obtained from the uniprot knowledgebase (www.uniprot.org). Marked sequences (*) indicate C-term. amidation.

\(b\) Charge state (\(z\)) of the peptide as detected by LC-MS/MS.

\(c\) The peptide mass to charge (\(m/z\)) is given for singly charged species. The observed masses refer to the MALDI imaging experiments.

\(d\) Mascot MS/MS ion scores obtained for the respective peptide.

Sequence verified striatal neuropeptides. The peptides were detected by means of MALDI IMS and sequence verified using off tissue LC-FTICR ESI-MS/MS.

1755; Fig 1D) that is exclusively observed in the striatum were visualized in FlexImaging together with the photomicrograph of the spotted section. The striatum from the ventral tip of the lateral ventricles, following the corpus callosum to the most ventral point of capsule externa delineated the upper border of the striatum, and a straight line between the two most ventral points separated the caudate putamen from the n. accumbens. This ventral border was bisected by a perpendicular line dividing the ROI into the DM and DL part. Only results consistent in all three replicate experiments are presented here (\(p < 0.05, \text{HD versus LD and HD versus LC, using } < 1\% \text{ false discovery rate})

High mass accuracy Fourier transform ion cyclotron (FT-ICR) mass spectrometry in conjunction with collision induced fragmentation of striatal peptide extracts, unequivocally confirmed the identity of several neuropeptides, including dynorphin B (DynB, \(m/z\) 1570.88), \(\alpha\)-neoeンドorphin (aNeo, \(m/z\) 1288.68), substance P (SP, \(m/z\) 1347.7), as well as Met-Enk-Arg (\(m/z\) 730.3), Met-Enk-Arg-Phe (\(m/z\) 877.4), Met-Enk-Arg-Gly-Leu (\(m/z\) 900.4), PENk (220–229; \(m/z\) 1367.5), PENk (198–209; \(m/z\) 1386.6) and PENk (219–229; \(m/z\) 1466.6) (Table I). Although MS/MS based sequence identification of rodent aNeo, SP and enkephalin peptides have been reported in previous studies (44, 45), the here presented data show the identification of several endogenous dynorphins that has not been described before (Fig. 2, Table I).

**Prodynorphin-Derived Peptides, but not Substance P, Correlate with LID Severity**—The most prominent changes were found in the dorsolateral part of the DA-denervated striatum. Both DynB and aNeo peak intensities were elevated by 50–60% in high dyskinetic animals compared with low dyskinetic animals and lesion controls (\(p < 0.05, F(2, 15) = 12.8 \text{ DynB, } F = 5.7 \text{ aNeo}\) (Fig. 3, Fig. 4A). For substance P, a small but significant increase of 11% in the lesioned dorsolateral striatum was observed (Fig. 4A). An up-regulation of prodynorphin mRNA levels in the dorsolateral striatum have been strongly associated with the severity of axial, limb, and orolingual dyskinesia (21). Simple regression analysis revealed that the peak intensities of both DynB and aNeo, but not substance P, were positively correlated with the sum of axial, limb, and orolingual dyskinesia (DynB: \(p < 0.001, \text{Pearson's correlation coefficient } r = 0.82; \text{aNeo: } p < 0.01, r = 0.68; \text{SP } p = 0.06, r = 0.51\) (Fig. 4B).

No significant change was observed for these peptides in the dorsomedial striatum. However, similar to prodynorphin mRNA (21), a slight elevation of dynorphin peptides (DynB and aNeo) was noted in the dorsomedial striatum in the two low dyskinetic animals that exhibited locomotive/rotational dyskinesia (Fig. 3A, arrowheads).

For the whole dorsal striatum a weaker but still significant increase of aNeo was observed in the high dyskinetic group compared with the low dyskinetic group (\(p < 0.05, \text{LD group } 0.96 \pm 0.007, \text{HD group } 1.48 \pm 0.24)\), however this difference depended mainly on the elevation in DL striata of HD animals. Similarly, a small elevation of SP, but not DynB, was also detected in the whole dorsal striatum (\(p < 0.05, \text{LD group } 0.93 \pm 0.029, \text{HD group } 1.09 \pm 0.027\).

**Dynorphin B Immunoreactivity Surrounds FosB-positive Nuclei**—Given the previously described co-expression of striatal PDyn mRNA and FosB-related proteins and their strong association with dyskinesia severity (Andersson et al., 1999), we asked if fully processed dynorphin peptides could be detected in the soma of striatal neurons. First we verified that the number of FosB/deltaFosB immunoreactive nuclei in the dorsolateral striatum was increased in high dyskinetic animals (F(1,14) = 4.7, \(p < 0.05\)) and correlated linearly with axial, limb, and orolingual dyskinesia (\(p < 0.01, r = 0.64\). Second, double antigen immunohistochemistry using antibodies against dynophin B peptides and FosB-related proteins was carried out on sections from two high-dyskinetic animals and...
one low dyskinetic animal. No FosB-immunolabeled nuclei were detected in the DA-denervated striatum of the low-dyskinetic animal, whereas the two high-dyskinetic animals showed distinctly higher striatal levels of both FosB-related proteins and dynorphin B immunoreactivity. To assess how many FosB-immunopositive cells also expressed DynB we counted 200 FosB-positive cells in each dorsolateral striatum of the high dyskinetic animals. Double-positive cells were defined as a FosB-immunoreactive nucleus (red) with dynorphin staining (green) distributed closely around it (Fig. 5).

Indeed, all FosB-positive cells were double-positive for DynB immunoreactivity in the DA-denervated striatum of high-dyskinetic animals (200/200 cells in both HD animals) (Fig. 5).

Des-tyrosine \(\alpha\)-Neoendorphin Metabolite Levels Correlate With Dyskinesia Severity—A peptide with \(m/z\) value of 1065.6 was significantly elevated by 58% in the DA-depleted dorsolateral striatum in high dyskinetic rats (Fig. 6A and 6B). The spatial intensity distribution was consistent with that of dynorphin B and \(\alpha\)-Neo, as demonstrated by multiplexing \(m/z\) 1065.6 (visualized in green) with \(\alpha\)-Neo (red) (Fig. 6A). Furthermore, simple regression analysis showed a strong correlation between \(m/z\) 1065.6 peak intensity values and dyskinesia scores (\(p < 0.01; r = 0.7\)) (Fig. 6C). The \(m/z\) 1065.6 corresponds to the removal of N-terminal tyrosine from \(\alpha\)-Neo, which was sequence validated by LC-MS/MS analysis of striatal peptide extracts (Fig. 6D). No other peptide with a mass of 1065.6 could be detected in the full scan mass spectra.

This prompted a search for other possible des-tyrosine dynorphins. The distribution of des-tyrosine dynorphin A (DynA 2–8, \(m/z\) 818.5) and dynorphin B (DynB 2–13, 1407.6) closely matched that of the corresponding intact dynorphin...
peptide both in the nucleus accumbens and in the dorsolateral striatum of a few HD animals (Fig. 7A). Furthermore, DynA (2–8) but not des-tyrosine DynB (2–13) could be identified by LC-MS/MS (Table I). However, simple regression analysis showed no correlation between peak intensity and LID severity for both peptide masses. The putative des-tyrosine peptide product of DynA (1–8) was found with higher peak intensity than the intact dynorphin peptide, indicating that bioconversion of DynA (1–8) had occurred to a high degree already 60 min after L-DOPA administration (Fig. 7A).

Detection of Other Dynorphin Related Peptides—Several dynorphin peptides could not be detected by MALDI IMS analysis, including \[M + H\]^+: m/z 2147.2 corresponding to DynA (1–17), and m/z 1602.9 (DynA 1–13). The C-terminal fragment of dynorphin A with m/z 1028 (DynA 10–17) was detected in a few HD animals and exhibited a similar spatial distribution pattern as DynB and aNeo. However, no consistent increase in HD animals was observed and simple regression analysis showed no correlation between peak intensity and dyskinesia severity. Interestingly, Leu-Enkephalin (YGGFL, m/z 556, LeuEnk or DynA 1–6), which was previously reported to be the main degradation product of striatal dynorphin B could not be detected (46).

Detection of Enkephalins—Most of the detected enkephalins showed no consistent change in abundance when comparing the HD to LD group. A 10% higher intensity of one enkephalin peptide, PEnk (220–229; m/z 1367.5) was detected in the dorsolateral but not medial striatum of HD animals (p < 0.05) (Fig. 7B). PEnk (220–229) does not include the amino acid sequence YGGFM/L necessary for binding and activation of opioid receptors, and the distribution did not match that of the L-DOPA-induced increase of dynorphins. By contrast, PEnk (220–229) was found to be predominantly distributed centrally of the striatum (Fig. 7B). A central cosecretion of the peptide together with other PEnk species in the intact striatum was reported in a previous peptidomic study using in vivo microdialysis followed by LC-MSMS (47). In addition, high levels of PEnk (220–229) peptide were observed in the target structure of the striatopallidal projection neurons, the globus pallidus of intact animals (Fig. 1A, visualized in purple). No consistent change was observed for Met-Enk-Arg-Phe, Met-Enk-Arg-Gly-Leu, PEnk (198–209), and PEnk (219–229) but a strikingly similar striatal distribution to PEnk (220–229) was observed in a few high dyskinetic animals (Fig. 7C), suggesting elevated pallidal levels of enkephalins in dyskinetic animals.

Striatal Dynorphin Peptide Validation by IMS of Pdyn KO Mice—For further validation of dynorphin peptide identities, we performed MALDI imaging on striatal sections from wild-
type control and Pdyn knockout mice (Fig. 8) (32). Characteristic localization of opioid peptides (αNeo, DynB and desTyr-αNeo) to the nucleus accumbens were observed in striatal sections of normal control mice similar to the results obtained for the intact striata of rat brain samples (Fig. 3). No dynorphin peptide peaks could be detected in the striatum of Pdyn knockout mice, whereas most peptides ion distribution patterns and abundances were no different from wild type control striatum, for example substance P and PEnk 220–229 (Fig. 8).

**DISCUSSION**

A core component of the patophysiology of LID is an increased activity of the direct striatal output pathway according to the traditional view of basal ganglia function (48, 49). These striatal medium-sized projection neurons connect with basal ganglia output regions using GABA as neurotransmitter and co-expressing prodynorphin and substance P mRNA. Indeed, increased level of striatal prodynorphin gene expression is one of the most consistent molecular changes associated with the development of LID in different animal models of PD (4, 5, 8, 50). In addition, antisense mediated knockdown of FosB-related proteins and a concomitant reduction in PDyn mRNA levels indicated a causal role of dynorphins in the development of LID over time (21). However, it has also been suggested that the L-DOPA-induced up-regulation of PDyn mRNA in the dopamine-depleted parkinsonian brain constitutes a homeostatic response of the dynorphin system in order to dampen behavioral exaggerations (51, 52). But it has been difficult to interpret the role of dynorphins in LID because the exact nature of prodynorphin processing products has not previously been determined.

The presented results are comprised of MS-based identification and investigation of LID-associated dynorphin processing products with high molecular specificity, which has not been reported before. The introduction of mass spectrometry to the field of comprehensive protein analysis, termed proteomics, has advanced the field significantly because MS offers high specificity while being relatively time and cost effective. The only two proteomic studies published so far on LID and PD employed two dimensional-differential gel electrophoresis (2D-DIGE), but because of limitation concerning analysis of low molecular weight compounds (>5 kDa), gel electrophoresis based proteomic studies do not permit the analysis of endogenous neuropeptides, such as the fully processed opioid peptides (53, 54). Furthermore, neuropeptide levels are often present in low amounts in the femtomolar range beyond the limits of detection of gel-based proteomics (55). Similarly, few mass spectrometry-based studies have assessed endogenous dynorphin peptides in the normal intact striatum (56–58) and previous studies on dynorphin metabolism were carried out on synthetic peptides that were infused into the intact or parkinsonian striatum or studied in vitro (46, 59, 60).

A typical obstacle in tissue proteomics and peptidomic studies is the loss of any spatial information beyond the size of the predetermined brain structure. This is highlighted in
a recent study using neuropsotidomic analysis to detect L-DOPA-induced changes in neuropeptide levels a mouse model of PD (44). Here, no dyskinesia was rated and the neuropeptides were extracted from the entire striatum. Only one PDyn derived peptide, PDyn (177–199) was found significantly elevated, possibly reflecting the fact that highly localized increases in peptide levels can be diluted beyond the level of detection if whole structures are analyzed. By contrast, the main feature of MALDI imaging MS is the preservation of spatial information at sub-millimeter level that allows post analysis assignment without a priori knowledge of the most relevant region of interest (61). However, it is equally possible to assign regions of interest centrally in striatum was observed in 4 out of 6 high-dyskinetic animals. The corpus callosum and anterior commissure was visualized by m/z 2028 (MBP fragment) in blue. C, Spatial distribution of other enkephalin peptides in one high dyskinetic animal. Although no statistical difference was observed in between the groups the peptides showed a characteristic localization similar to PENk (220–229).

In the present study, chronic intermittent L-DOPA induced higher levels of dynorphin B, α-neoendorphin, and substance P neuropeptides in the dorsolateral striatum of animals that displayed predominantly severe axial, limb, and orolingual dyskinesia. In the dorsolateral striatum, the peak intensities of both DynB and aNeo, but not SP, positively correlated with LID severity. This is in accordance with previous studies on Prodynorphin mRNA distribution (5, 21). In addition, dynor-
phin B-immunoreactive striatal cells have been observed in a mouse model of LID (65). Other studies have shown that relatively high doses of L-DOPA (100 mg/kg per day) or repeated apomorphine treatment induced high levels of striatal DynA(1–8) and DynA(1–17) immunoreactivity, however DynB and aNeo were not assessed in these studies (66, 67). We did not observe any L-DOPA-induced regulation of dynorphin A-related peptides, and probably this is partly because of the relative low dose L-DOPA used in the present study (8 mg/kg per day) and partly because of the moderate number of animals.

Sometimes mRNA based measurements do not reflect the levels of proteins or peptides. For example, PDyn mRNA levels are reduced by 40–50% in the DA-denervated striatum of the rat model of PD (5, 21), whereas the dynorphin peptide levels remain unchanged compared with the intact striatum (lesion controls in Fig. 4 (14–16)). The reduction of PDyn mRNA synthesis is probably not surprising, as this reflects the reduced activity of PDyn-expressing medial spiny neurons in the parkinsonian brain. Reduced activity means less release of dynorphin peptides, therefore there is no requirement to replenish dynorphins and PDyn transcription can be reduced.

Traditionally propeptide processing into the mature neuropeptide is thought to occur during the axonal transportation of the propeptide to its target release area. A recent study indicates that a significant amount of processing occurs in axonal terminals and dendrites, as the intact 14-kDa prodynorphin propeptide has been detected in dense core vesicles in hippocampal mossy fibers (38). In order to assess the cellular distribution of L-DOPA-induced DynB, double antigen immunohistochemistry was performed. L-DOPA-induced FosB-immunopositive neuronal nuclei were surrounded by high levels of DynB immunoreactivity and the close proximity of fully mature DynB to the nuclei indicated that substantial dynorphin propeptide processing occurs relatively early after translation. Interestingly, MALDI IMS could not detect any precursor species such as big dynorphin (Big DynAB 1–32, m/z 3982.25) and leumorphin (dynorphin B 1–29; m/z 3317.6). However the regional location of the striatal full-length propeptide (14–15 kDa) remains elusive as another MALDI IMS protocol would have to be applied for its detection (24). The presence of L-DOPA-induced elevation of fully processed aNeo and DynB in striatum indicates that these dynorphins may be released locally upon dopaminergic stimulation.

The endogenous dynorphins mainly display high affinity to the kappa opioid receptor (KOP), but can also interact with the other classical opioid receptors mu (MOP) and delta (DOP) with somewhat lower binding affinities (68, 69). In particular the shorter dynorphins, such as aNeo, display the least selectivity being active in the nanomolar range at both DOPr and MOPr (68). The present study shows that prodynorphin processing in the striatonigral projection neurons mainly results in DynB and aNeo that may result in abnormal signaling through
the delta and mu opioid receptor instead of KOP receptors. Indeed, both DOPr and MOPr-antagonists attenuate LID in the MPTP-lesioned marmoset (4). Along the same line of reasoning it may not be surprising that several studies have reported anti-dyskinetic effects of kappa-agonist administration in rat and monkey models of PD, however in some studies the anti-parkinsonian effect of l-DOPA was also diminished and side-effects reduced the therapeutic value (70–72). This also highlights the problem of opioid agonist or antagonist therapy that inevitably affects receptors outside the intended target area and calls for a search for molecular changes uniquely associated with dyskinesia.

Opioid receptor binding assays provide some insight into striatal and striatonigral opioid transmission associated with dyskinesia. In the rat model of LID in PD, the DA-denervation induced a decrease in striatal MOP and DOP receptor binding, but only striatal KOP receptor binding was negatively correlated with LID (73). By contrast, there was no correlation with striatal KOP, DOPr, or MOPr, binding and LID in the MPTP-model of macaque monkey (8). In both these studies significant negative correlations between dyskinesia and KOP and MOP receptor-binding in basal ganglia output structures indicated increased striatonigral opioid transmission in dyskinesia, whereas opioid receptor binding in the striatum was less associated with LID severity. Taken together, this indicates that DynB and aNeo mainly act in SN through opioid receptor binding but that the role of opioid transmission in the striatum remains unclear.

In the study presented here the animals were sacrificed at the time when the rats exhibit most dyskinesia, 1 h after the last l-DOPA injection, in order to detect dynorphin metabolites by MALDI IMS. No evidence was found of striatal neuropeptides and indicate a biologically relevant dissociation in dynorphin bioconversion in striatum compared with the substantia nigra, which is in accordance with previously published results from normal intact rat brain (46). No other dynorphin-derived C- or N-terminal fragments could be detected in the striatum by MALDI IMS analysis, further substantiating that des-tyrosine dynorphins are not produced by unspecific enzymatic degradation. MALDI MS analysis of synthetic dynorphin peptides (20 nmol on target) did not reveal in source fragmentation resulting in loss of the N-terminal tyrosine. Furthermore, if the des-tyrosine aNeo is a product of in source decay the correlation coefficient of individual pixel peak intensities between aNeo and des-tyrosine aNeo would be close to 1. Similarly the correlation coefficient between the first and second isoforme of dynorphins would be close to 1, and indeed the Pearson R ranged from 0.93 to 0.97 for the first and second isoforme of des-tyrosine aNeo, aNeo, and dynB. A higher correlation coefficient was found between aNeo and des-tyrosine aNeo (0.83) than between des-tyrosine aNeo and dynorphin B (0.62) or the unrelated proenkephalin 220–229 (0.17) that was used as a negative control. The close, but not perfect linear relationship between des-tyrosine aNeo and aNeo may also indicate that the removal of tyrosine occurs after synaptic release rather than as part of the process of neuropeptide maturation. One other potential mechanism of striatal des-tyrosine dynorphins functionality might be the based on nonopioid receptor-dependant interactions with striatal NMDA receptors (79–82). As such, the des-tyrosine dynorphins may constitute a functional compensatory mechanism for countervailing l-DOPA-induced overstimulation of striatal DA D1 receptors. One of the objectives in the field of LID research must to dissociate between l-DOPA-induced anti-parkinsonian and dyskinesiogenic effects and to find novel molecular targets, such as the des-tyrosine dynorphins, in order to tailor new pharmaceutical interventions to block the development or maintenance of LID.

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Dynorphin Peptide Alterations in L-DOPA-induced Dyskinesia

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Dynorphin Peptide Alterations in L-DOPA-induced Dyskinesia


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Dynorphin Peptide Alterations in L-DOPA-induced Dyskinesia

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