Increased putamen hypercapnic vasoreactivity in levodopa-induced dyskinesia

Vincent A. Jourdain,1 Katharina A. Schindlbeck,1 Chris C. Tang,1 Martin Niethammer,1,2 Yoon Young Choi,1 Daniel Markowitz,1 Amir Nazem,1 Dominic Nardi,4 Nicholas Carras,4 Andrew Feigin,1,2 Yilong Ma,1 Shichun Peng,1 Vijay Dhawan,1 and David Eidelberg1,2

1Center for Neurosciences, Feinstein Institute for Medical Research, Manhasset, New York, USA.
2Department of Neurology, Northwell Health, Manhasset, New York, USA. 3Hofstra Northwell School of Medicine, Hempstead, New York, USA. 4Department of Anesthesiology, Northwell Health, Manhasset, New York, USA.

Introduction

Levodopa treatment for Parkinson’s disease (PD) is complicated by potentially disruptive involuntary movements following drug administration. These movements, termed levodopa-induced dyskinesia (LID), are seen in approximately 50% of PD patients who received the drug for 5 years and in nearly all patients after 10 years of treatment (1). While the mechanism of LID is not precisely known, experimental evidence from the 6-hydroxydopamine (6-OHDA) rat model has implicated neurovascular dysregulation in dopaminergically denervated brain regions as a major factor underlying the development of levodopa-mediated involuntary movements (2). Evidence for this hypothesis has been provided by recent dual-tracer PET studies conducted in human PD subjects (3, 4) and in the rodent model (5, 6). In brief, levodopa administration is associated with increases in local cerebral blood flow (CBF) and with simultaneous reductions in cerebral glucose metabolic rate (CMR) in the same brain regions. Dissociation of local vasomotor and metabolic drug responses (referred to as “regional dissociation”) has been observed in a rodent model of Parkinson’s disease (PD), levodopa-induced involuntary movements have been linked to striatal angiogenesis — a process that is difficult to document in living human subjects. Angiogenesis can be accompanied by localized increases in cerebral blood flow (CBF) responses to hypercapnia. We therefore explored the possibility that, in the absence of levodopa, local hypercapnic CBF responses are abnormally increased in PD patients with levodopa-induced dyskinesias (LID) but not in their nondyskinetic (NLID) counterparts. We used H215O PET to scan 24 unmedicated PD subjects (12 LID and 12 NLID) and 12 matched healthy subjects in the rest state under normocapnic and hypercapnic conditions. Hypercapnic CBF responses were compared to corresponding levodopa responses from the same subjects. Group differences in hypercapnic vasoreactivity were significant only in the posterior putamen, with greater CBF responses in LID subjects compared with the other subjects. Hypercapnic and levodopa-mediated CBF responses measured in this region exhibited distinct associations with disease severity: the former correlated with off-state motor disability ratings but not symptom duration, whereas the latter correlated with symptom duration but not motor disability. These are the first in vivo human findings linking LID to microvascular changes in the basal ganglia.
The underlying cause for the observed neurovascular changes in LID is not known. Experimental findings from the dyskinetic 6-OHDA rat model suggest a relationship between enhanced vasomotor responses to levodopa in the striatum and underlying angiogenesis (12, 13). Although some evidence for angiogenesis in human PD has been provided by the analysis of postmortem tissue and cerebrospinal fluid (14–16), the specificity of the observed changes for LID remains uncertain. Indeed, the demonstration of localized angiogenesis in the living human brain represents a major challenge, given the lack of sensitive imaging methods to detect and quantify the process in small anatomical regions in the absence of tumor.

In this study, we used an indirect approach based upon a transgenic mouse model of inborn angiogenesis secondary to overexpression of VEGF (17). Vogel and colleagues found that increases in capillary density in angiogenic brain regions were associated with relatively normal resting CBF under routine normocapnic (NC) conditions. However, with the induction of vasodilation by hypercapnia (HC), significant increases in local CBF were observed in areas of vascular proliferation, without corresponding changes in local metabolic activity. In a similar vein, HC vasoreactivity has recently been used in human subjects as a means of assessing angiogenesis in brain tumors (18). We therefore used $H_2^{15}O$ PET to quantify HC CBF responses in PD subjects with and without LID who were scanned in the unmedicated (“off”) state.

We predicted that, because of underlying angiogenesis, HC vasoreactivity measured in the previously determined basal ganglia dissociation region (4) would be greater in LID subjects than in their age- and sex-matched patient counterparts without this complication of levodopa treatment or in healthy subjects. Given that angiogenesis in levodopa-treated PD patients is likely to increase with advancing dopaminergic denervation (4, 16), we additionally predicted that the putamenal HC response would correlate with clinical indices of disease progression.

**Results**

**Putamen HC responses are abnormally increased in LID subjects.** Globally normalized CBF increased with HC when measured off medication in the areas of levodopa-mediated dissociation that were previously reported in the putamen (Figure 1A), internal globus pallidus (Figure 2A), and pons (Figure 2B) (3, 4). In each of these regions, significant HC CBF responses were observed in LID, nondyskinetic (NLID), and healthy control subjects ($P < 0.05$; paired Student’s $t$ tests). Analogous changes, however, were not seen in the ventrolateral thalamic dissociation region (Figure 2C) in any of the participant groups. Globally normalized
CBF values measured in the NC, unmedicated baseline condition did not differ significantly across groups in any of the dissociation regions \( F(2,33) < 0.58, P > 0.57; \) 1-way ANOVA. Likewise, group differences in global CBF were not significant when assessed in the baseline condition \( F(2,33) = 2.08, P = 0.1414 \).

Of the levodopa dissociation regions (LDDRs), the putamen alone (Figure 1B) exhibited a significant group difference in HC vasoreactivity \( F(2,33) = 6.64, P = 0.0038; \) 1-way ANOVA. CBF responses in this region were greater in LID subjects compared with NLID subjects \( (P = 0.008) \) as well as healthy control subjects \( (P = 0.013) \). We further observed that in this region the expected HC CBF response \( (\text{CBF}_{\text{HC}} > \text{CBF}_{\text{NC}}) \) was not present in two \( (1 \text{ NLID} \text{ and } 1 \text{ control}) \) of the 36 study participants. Nonetheless, excluding these “violators” did not alter the significance of the findings \( F(2,31) = 5.76, P = 0.0144 \). Local HC CBF responses measured in the other LDDRs (Figure 2, A–C, right) were likewise not significant \( (P > 0.27; \) 1-way ANOVAs).

Of the levodopa dissociation regions (LDDRs), the putamen alone (Figure 1B) exhibited a significant group difference in HC vasoreactivity \( F(2,33) = 6.64, P = 0.0038; \) 1-way ANOVA. CBF responses in this region were greater in LID subjects compared with NLID subjects \( (P = 0.008) \) as well as healthy control subjects \( (P = 0.013) \). We further observed that in this region the expected HC CBF response \( (\text{CBF}_{\text{HC}} > \text{CBF}_{\text{NC}}) \) was not present in two \( (1 \text{ NLID} \text{ and } 1 \text{ control}) \) of the 36 study participants. Nonetheless, excluding these “violators” did not alter the significance of the findings \( F(2,31) = 5.76, P = 0.0144 \). Local HC CBF responses measured in the other LDDRs (Figure 2, A–C, right) were likewise not significant \( (P > 0.27; \) 1-way ANOVAs). Of note, HC CBF responses recorded
in the putamen dissociation region correlated with corresponding levodopa-mediated vasomotor changes measured in the same brain region ($r = 0.483$, $P < 0.01$; Pearson’s correlation). Analogous correlations were not present for the local changes measured in the other dissociation regions ($P > 0.19$).

**HC responses in the putamen distinguish LID from NLID — voxel-wise analysis.** To confirm these findings, we additionally conducted a whole-brain analysis that was not restricted to the previously identified LDDRs. In this data-driven analysis, we interrogated the entire brain volume for clusters with significant group (LID/NLID) × condition (HC/NC) interaction effects on local CBF values (see Methods). The analysis revealed the presence of only two significant clusters — both situated in the posterior putamen. The first cluster (Figure 3A, orange-yellow) was centered ventrally at $-34$, $-10$, $-6$ in close proximity (Euclidean distance $= 2.8$ mm) to the previously identified putamen dissociation region (4) (Figure 3A, black contours). Local CBF in the ventral cluster (Figure 3B) increased significantly with HC in LID ($P < 0.00001$), NLID ($P < 0.02$), and healthy control subjects ($P < 0.0008$; paired Student’s $t$ tests), with a minimal number of violations in each group. HC CBF responses recorded in this cluster (Figure 3C) differed significantly across groups ($F (2,33) = 6.62$, $P = 0.0038$; 1-way ANOVA), with greater CBF increases in LID subjects compared with NLID subjects ($P < 0.004$), but only marginal differences with regard to normal values ($P = 0.055$; post-hoc Bonferroni tests).
The second cluster was centered dorsally at –34, –4, 2 and was spatially distinct from the putamen dissociation region (Euclidean distance = 7.2 mm). As in its ventral counterpart, the dorsal cluster exhibited significant HC CBF responses (data not shown) in each of the three groups ($P < 0.001$; paired Student’s $t$ tests). Group differences in the local HC CBF response were significant in the dorsal putamen cluster [$F(2,33) = 3.50, P = 0.0417; 1$-way ANOVA]. The size of this effect was weaker dorsally than in its ventral counterpart, with only modestly increased HC responses in LID subjects compared with NLID subjects ($P < 0.04$; post-hoc Bonferroni test).

Vasomotor response to HC in the sensorimotor cortex. In a previous study (4), we additionally identified a discrete area within the sensorimotor cortex (SMC) in which baseline (off-state) metabolic activity was significantly elevated in LID subjects compared with NLID subjects (see Methods). In addition to the significant vasomotor levodopa responses noted previously in this area, we now observed consistent CBF increases with HC ($P < 0.001$; paired Student’s $t$ test). Nonetheless, in contrast to the putamen, HC CBF responses in the SMC (Figure 4B) exhibited only a marginal difference across groups [$F(2,33) = 2.63, P = 0.087, 1$-way ANOVA]. No significant correlation between local HC and levodopa-mediated CBF responses was observed in this SMC region ($r = 0.22, P = 0.96; Pearson’s correlation$).

Clinical/imaging correlations. We examined the relationship between local vasomotor responses measured in the putamen LDDR and clinical descriptors of disease progression obtained in the individual PD subjects. Correlation analyses (Table 1) showed that HC CBF responses in the putamen LDDR area correlated with the off-state Unified Parkinson’s Disease Rating Scale (UPDRS) motor ratings ($r = 0.513, P < 0.02; Pearson’s correlation$) and not with symptom duration ($r = 0.161, P = 0.453$). Given that motor ratings and disease duration were intercorrelated in this PD sample ($r = 0.428, P < 0.05$), we used partial correlation analysis to isolate the effects of each clinical covariate while controlling for individual differences in the other covariate. After adjusting for the effects of duration, HC CBF responses in the putamen dissociation region (Figure 5A, left) correlated significantly with off-state UPDRS motor ratings ($r = 0.465, P < 0.03; partial correlation$). That said, taking individual differences in off-state motor ratings into account (Figure 5A, right), the correlation of HC responses in this region with symptom duration was not significant ($r = 0.217, P = 0.99; partial correlation$).

In contrast to the HC response in the putamen dissociation region, vasomotor levodopa responses measured in the same region were found to correlate with duration ($r = 0.592, P < 0.003; Pearson’s correlation$) but not with off-state UPDRS motor ratings ($r = 0.335, P = 0.12$). Indeed, controlling for variation in the off-state motor ratings, local vasomotor responses to levodopa (Figure 5B, right) correlated strongly with duration ($r = 0.739, P < 0.0003; partial correlation$). However, after adjusting for the effects of duration
(Figure 5B, left), the correlation with off-state motor rating values remained nonsignificant ($r = 0.02, P = 0.89$; partial correlation). A similar “double dissociation” was observed for the partial correlations of HC and levodopa-mediated CBF responses recorded in the ventral putamen cluster (Figure 3A) with the corresponding clinical progression measures.

**Discussion**

Dissociation of vasomotor and metabolic responses to levodopa has been noted as a consistent feature of acute drug administration in human PD (3, 4) and in the 6-OHDA rat model (5, 6). This phenomenon is closely linked to levodopa-mediated increases in local CBF, likely related to engagement of D1 receptors on blood vessels apposed to dopamine terminals in the mammalian striatum (8, 9, 19). While the magnitude of the putamen vasomotor levodopa response is greater in dyskinetic PD subjects (4) and 6-OHDA rats (5), significant dissociation effects have been documented in both species whether or not abnormal involuntary movements were concurrently elicited by the drug (3, 6). This contrasts with the development of angiogenesis in the chronically levodopa-treated 6-OHDA rodent, wherein localized microvascular pathology is closely linked to the appearance of dyskinesia (12, 13, 16). Given the immaturity of angiogenic blood vessels, the increases in local CBF induced acutely by levodopa may lead to transient stretching of the endothelial lining and consequent changes in blood-brain barrier permeability (2, 5). Such effects, needless to say, are unlikely to occur in areas with normally developed capillary endothelium (4). While this hypothesis may explain key features of striatal levodopa transport in the dyskinetic rodent model, evidence for angiogenesis in human PD is comparatively limited (14–16).

To address this issue, it would be desirable to identify and measure localized angiogenesis in living LID subjects. While a variety of techniques are under development to image angiogenesis, most are designed for oncologic use. Indeed, in contrast to tumor angiogenesis, the degree of localized vascular proliferation anticipated in PD subjects with LID is likely to be relatively mild. Moreover, in the current study, we sought to quantify vascular changes in the putamen LDDR, a relatively small brain region that was identified using functional imaging (3, 4), but which was normal on routine anatomical MRI. Given these challenges, we chose an indirect functional approach in which local HC CBF responses were mapped using a standard $^{15}$O PET technique. The strategy was based upon prior experimental findings from the transgenic VEGF overexpression mouse model (17). In these animals, localized angiogenesis in the brain was associated with increased HC CBF in the same areas. Indeed, in this model, CBF measured under HC conditions correlated with local capillary density, supporting the use of the measure as a quantitative descriptor of underlying vascular proliferation.

In contrast to the local vasomotor response to levodopa, which is likely driven by the engagement of endothelial D1 receptors, CO2-mediated vasodilation is regulated downstream by the effects of nitric oxide on vascular tone (20, 21). We note that, while the HC CBF response appears to be sensitive to local capillary density (see above), the vasomotor levodopa response likely is also influenced to some degree by this

| Table 1. Clinical correlates of hypercapnic and dopaminergic CBF responses |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| **Disease duration** | **LDD(w) (mg/kg/d)** | **UPDRS (off)** | **Putamen LDDR (±34, -8, -4)** | **Sensorimotor cortex (-58, -18, 28; 52, -20, 26)** |
| Age | $0.035^a$ | $-0.215$ | $0.102$ | $0.361$ | $-0.174$ | $0.409^a$ | $0.022$ |
| Disease duration | $0.211$ | $0.428^a$ | $0.592^a$ | $0.229$ | $-0.004$ | $0.129$ | $-0.466^a$ |
| LDD(w) (mg/kg/d) | $0.112$ | $0.335$ | $0.513^a$ | $0.483^a$ | $0.466^a$ | $0.044$ |
| UPDRS (off) | $0.079$ | $0.284$ | $-0.011$ |

$^a$Pearson product-moment correlation coefficient. $^bP < 0.05, ^cP < 0.01$, Pearson’s correlation. LDD(w), weight-corrected levodopa daily dose; UPDRS (off), Unified Parkinson’s Disease Rating Scale motor (Part III, off-state) rating (31); LDDR, levodopa dissociation regions (4); $\Delta_{HC}$, hypercapnic cerebral blood flow (CBF) response ($\Delta_{HC} = CBF_{HC} - CBF_{NC}$); $\Delta_{DA}$, dopaminergic CBF responses to levodopa ($\Delta_{DA} = CBF_{ON} - CBF_{OFF}$).
factor. It is therefore perhaps not surprising that in the PD subjects a significant correlation between the two response measures was observed in the putamen, wherein VEGF upregulation and increased microvascular density have both been documented in postmortem samples (14, 16). We further note that significant HC and levodopa-mediated CBF responses were additionally seen in other brain areas, such as the pallidal and pontine LDDRs and the previously identified “LID-related” region in the SMC (4). Correlations between local response measures in individual regions were not significant, however, outside the putamen. Further studies are needed to determine the specificity of the association for angiogenesis in different brain areas.

While the HC and levodopa-mediated CBF responses in the putamen LDDR are significantly related, this correlation was modest, accounting for less than 25% of the overall variance. Indeed, we noted a remarkable difference in the clinical correlates of the two measures. Specifically, HC responses in this region correlated with clinical severity, as measured by off-state UPDRS motor ratings, but not with symptom duration. This contrasted with the vasomotor levodopa responses in the same region, which correlated with duration but not with motor ratings. Indeed, this “double dissociation” was highlighted by the leverage plots, which displayed the correlations adjusted for mutual interactions between the response measures on one hand and between the clinical regressors on the other. The results of this analysis accord with our earlier observation that vasomotor responses to levodopa in the putamen are associated with longer disease duration (4). Given that levodopa treatment was initiated early in these patients, we were not able to determine the degree to which this relationship was influenced by levodopa exposure as opposed to symptom duration. Even so, the weight-corrected daily levodopa dose [LDD(w)], which functioned as a proxy for the aggregate amount of the drug that the subject received over time (4), had no effect on the results of the model. Similarly, no relationship was discerned between LDD(w) values and vasoreactivity to levodopa or HC measured in the putamen LDDR.

Recent epidemiologic findings support the differential roles for disease duration and severity in the pathogenesis of LID (22). In this context, the motor UPDRS can be construed as the clinical counterpart of putamen dopaminergic denervation. This is also in line with the consistent correlation of off-state motor ratings with loss of dopaminergic signal in the putamen, as measured using PET or single-photon emission computed photography methods (23–25). By contrast, correlations with duration (corrected for individual differences in off-state motor ratings) assess relationships with the chronicity of disease, duration of treatment, or a combination of the two variables. Thus, as an index of capillary reserve and underlying...
microvascular proliferation, HC responses in the putamen correlated with the pathological feature most intimately linked to focal angiogenesis in the dyskinetic rat model, namely nigrostriatal dopamine denervation (12, 13, 16), and with the clinical counterpart of these changes in humans, namely off-state UPDRS motor rating (22). The dopaminergic vasomotor response measured in the putamen relates analogously to disease duration in a particular PD patient. This measure captures the acute effect of levodopa administration on putamen CBF, which is dominated by direct vasomotor effects of the drug on the vessel wall (7, 8). The current findings extend our prior observations relating vasomotor levodopa responses in the putamen to disease duration (3, 4). Based on the data, it is tempting to relate dopaminergic CBF responses in this region to local upregulation of vascular D1 receptors, which may increase as a function of disease duration. The local HC response, by contrast, is specifically associated with the changes in capillary density that develop regionally through angiogenesis. Both effects, notably, are exaggerated in individuals with LID, suggesting that this complication of treatment is mediated through a convergence of the two mechanisms.

We have previously found that levodopa-mediated dissociation effects are localized to brain areas that express dopa decarboxylase, which therefore can convert exogenous levodopa to dopamine (3). That said, key regions associated with LID exhibited substantial loss of dopaminergic input as part of the disease process as well as commensurate metabolic increases in target regions (3, 4, 26). This combination of effects may constitute a potent stimulus for angiogenesis in specific brain regions (4, 27). Indeed, the increases in dopaminergic and HC CBF responses seen in LID subjects are located within the area of elevated resting-state metabolic activity in the basal ganglia that has been noted as a consistent underlying feature of the disorder (3, 28, 29).

While the current data implicate angiogenesis as a major factor in the development of LID, its role remains to be confirmed. That said, vascular proliferation may represent an effective target to delay or even prevent the development of LID in PD patients. Therapies designed to attenuate the dopaminergic vasomotor response may be beneficial in this regard. Angiogenesis induced by levodopa in the 6-OHDA rat model is dependent on the stimulation of D1 receptors as well as activation of extracellular signal–regulated kinases (ERK1/2) (12). Selective D1 antagonist drugs may therefore be used to block the acute vasoreactive effects of levodopa while inhibiting the angiogenic process itself (2). Along these lines, recent evidence from the rotenone model suggests that nonsteroidal antiinflammatory drugs, such as ibuprofen/piroxicam, can retard the development of LID by reducing local VEGF and COX-2 levels (30). It remains to be seen whether these or other antiangiogenic strategies will be useful in mitigating LID in levodopa-treated PD patients.

Methods

Subjects. We studied 24 PD subjects (18 men and 6 women; age 63.3 ± 9.0 [mean ± SD] years; duration 8.2 ± 5.9 years; baseline off-state UPDRS motor ratings 22.4 ± 5.8). The diagnosis of PD in these subjects was made according to the UK Brain Bank Criteria for idiopathic PD (31). All subjects exhibited greater than 20% improvement in UPDRS motor ratings following a single oral dose of carbidopa/levodopa.

The PD subjects underwent individually titrated intravenous levodopa infusion as described elsewhere (3). Patients were divided into two groups based on whether observable dyskinesias were elicited during the infusion. The demographic and clinical features of the subjects in each group are presented in Table 2. The NLID group comprised 12 subjects (9 men and 3 women; age 65.0 ± 9.6 years; duration 6.1 ± 5.9 years; UPDRS motor ratings 19.5 ± 3.1) who had stable responses to levodopa infusion (0.55 ± 0.30 mg/kg/h) that improved motor symptoms (change in UPDRS motor ratings 7.8 ± 5.0; 41.4% ± 24.8%) without dyskinesia. The LID group comprised the remaining 12 subjects (9 men and 3 women; age 61.6 ± 8.6 years; duration 10.3 ± 5.5 years; UPDRS motor ratings 26.2 ± 4.5), in whom levodopa infusion (0.89 ± 0.46 mg/kg/h) improved motor symptoms (change in UPDRS motor ratings 12.3 ± 2.7; 47.8% ± 11.8%) while concurrently giving rise to sustained dyskinesias. The two groups did not differ significantly in age or sex (P > 0.36). While symptom duration was longer in the LID subjects than in the NLID subjects (LID: 10.3 ± 5.5 years; NLID: 6.1 ± 5.9 years), this difference was of only marginal significance (P = 0.08; Student’s t test). Differences between groups in the levodopa infusion rate needed to achieve maximal clinical improvement and in the mean change in UPDRS motor ratings during the infusion did not reach significance (P > 0.06).

PET. PD patients in both groups were studied in the baseline off-levodopa state with H215O PET to map CBF under NC (pCO2 = 41.06 ± 4.17 mmHg) and in a HC condition (HC: pCO2 = 45.30 ± 4.60 mmHg) achieved after 1 minute of 5% CO2 rebreathing under anesthesiology supervision (32). CBF maps from LID and NLID patients obtained under the NC and HC conditions were compared with corresponding
Table 2. Demographic and clinical data for Parkinson’s disease subjects

<table>
<thead>
<tr>
<th></th>
<th>NLID</th>
<th>LID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>65.0 (9.6)</td>
<td>61.6 (8.6)</td>
</tr>
<tr>
<td>Age at onset (yr)</td>
<td>58.9 (12.3)</td>
<td>51.3 (7.5)</td>
</tr>
<tr>
<td>Sex</td>
<td>9 male, 3 female</td>
<td>9 male, 3 female</td>
</tr>
<tr>
<td>Duration (yr)</td>
<td>6.1 (5.9)</td>
<td>10.3 (5.5)</td>
</tr>
<tr>
<td>UPDRS (off)</td>
<td>19.5 (5.1)</td>
<td>26.2 (4.5)</td>
</tr>
<tr>
<td>ΔUPDRS (%)</td>
<td>41.4 (24.8)</td>
<td>47.8 (11.8)</td>
</tr>
<tr>
<td>H&amp;Y, off-state</td>
<td>1.9 (0.4)</td>
<td>2.2 (0.4)</td>
</tr>
<tr>
<td>LDD (mg/d)</td>
<td>391.7 (212.0)</td>
<td>552.1 (242.3)</td>
</tr>
<tr>
<td>LDD(w) (mg/kg/d)</td>
<td>4.606 (2.049)</td>
<td>6.488 (2.094)</td>
</tr>
<tr>
<td>LEDD (mg/d)</td>
<td>574.2 (287.6)</td>
<td>817.8 (283.0)</td>
</tr>
<tr>
<td>LEDD(w) (mg/kg/d)</td>
<td>6.757 (2.658)</td>
<td>9.753 (2.035)</td>
</tr>
</tbody>
</table>

*Data are presented as mean (SD). ΔP < 0.001, ΔP < 0.05, ΔP < 0.01; Student’s t tests for comparison of LID versus NLID. LID, Parkinson’s disease subjects with levodopa-induced dyskinesia; NLID, Parkinson’s disease subjects without LID; UPDRS (off), Unified Parkinson’s Disease Rating Scale motor (Part III, off-state) rating (31); H&Y, Hoehn and Yahr stage; LDD, levodopa daily dose; LDD(w), weight-corrected levodopa daily dose; LEDD, levodopa equivalent daily dose (33); LEDD(w), weight-corrected levodopa equivalent daily dose.

maps generated in 12 age- and sex-matched healthy control subjects (9 men and 3 women; age 61.7 ± 8.0 years) who were scanned under analogous experimental conditions (NC: pCO₂ = 40.36 ± 4.75 mmHg; HC: pCO₂ = 44.10 ± 6.14 mmHg).

In all subjects, H₂¹⁵O PET scans were acquired in 3D mode using the GE Advance Tomograph (General Electric) at the Feinstein Institute for Medical Research. To map CBF in the NC and HC conditions, each subject was scanned with H₂¹⁵O PET in the unmedicated off-state. For each experimental condition, a 90-second CBF image was acquired following the injection of 10-mCi radiotracer. To compare CBF responses to HC with those induced in the same subjects by levodopa infusion on the same day, the PD subjects additionally underwent H₂¹⁵O PET scanning under NC during an intravenous levodopa infusion (mean infusion rate: 0.74 ± 0.43 mg/kg/h) titrated to achieve maximal motor improvement in individual subjects (change in UPDRS motor ratings: 10.0 ± 4.5; 44.6% ± 19.3%). Limited CBF data from 16 of the PD subjects obtained at baseline and during levodopa infusion have been reported previously (4).

Image processing was performed using SPM5 software (http://www.fsl.fmrib.ox.ac.uk/spm/software/spm5/; Welcome Department of Cognitive Neurology, University College, London, UK) implemented in Matlab 7.0.1 (MathWorks). The scans from each subject were realigned, spatially normalized, and smoothed with an isotropic Gaussian kernel (full width at half maximum 15 mm) to improve signal-to-noise ratio.

Data analysis. We have previously found that local vasomotor and metabolic responses to levodopa are consistently dissociated in the putamen, internal globus pallidus, ventral thalamus, and dorsal pons of PD patients (3, 4). To assess HC vasoreactivity in these LDDRs, we defined volumes of interest (VOIs) corresponding to the stereotaxic coordinates of these previously identified brain areas (4). In this study, VOIs for each LDDR were automatically positioned on the aligned CBF maps obtained under NC and HC conditions in the off-state. Globally normalized CBF values were recorded for each LDDR under these conditions and in a NC on-state obtained during an individually titrated levodopa infusion as described in detail elsewhere (3). Values were averaged for VOIs obtained at peak voxel and at the mirror coordinates on the opposite hemisphere. Based on these measurements, we computed the HC CBF response (ΔCBF = CBF_HC - CBF_NC) in each subject for the individual LDDRs and for the separate LID-related region that was previously identified bilaterally in the SMC (4). ΔCBF values for each region were compared across the LID, NLID, and control groups. These values were additionally correlated with corresponding dopaminergic CBF response (ΔDA = CBF_ON - CBF_OFF) obtained independently in the PD subjects.

Voxel-wise searches for areas with increased HC response in LID versus NLID subjects. In addition to hypothesis-based comparisons of ΔHC responses in prespecified LDDRs areas, we interrogated scan data from the entire brain for other areas in which these responses differed significantly for LID versus NLID subjects. Thus, we conducted whole-brain voxel-wise searches for clusters with significant group (LID/NLID) × condition (HC/NC) interaction effects. Given the exploratory nature of this analysis, clusters were considered significant at a threshold of P < 0.001 (voxel-level, uncorrected) with a cluster cutoff of 100 voxels. Spherical VOIs (radius = 3 mm) were used for post-hoc measurement of local CBF in the NC and HC conditions and ΔHC values in the regions with significant interaction effects.

Clinical correlates. To explore potential relationships between HC vasoreactivity measured in the previously specified LDDRs and in a SMC region in which baseline (off-state) CBF and metabolic activity were abnormally elevated in LID subjects (4) and clinical indices of disease progression, we correlated regional ΔHC values with symptom duration (as reported by the patient and/or the clinical record) and baseline motor disability (off-state UPDRS III ratings) obtained at the time of the study. We additionally evaluated correlations of the HC CBF response with the LDD(w) determined at the time of the study. This measure significantly correlated (r = 0.76, P = 0.001) with accumulated levodopa exposure in 15 of the PD subjects (6 NLID, 9 LID) for whom detailed medication histories were available. LDD(w) has been used...
as a clinical covariate in prior LID studies (4, 22). Relationships between the disease progression measures and local vasomotor responses to HC (ΔHC) and levodopa (ΔDA) in each of the LDDRs were evaluated using multiple regression analysis. Regression models were constructed based upon single and multiple predictor variables. The effect of each predictor on the regional drug or HC response was assessed graphically using leverage plots (partial correlations) in which the residuals for the dependent variable were plotted against those for each of the predictors after removing the other effects in the model.

Statistics. Differences in demographic features and clinical measures among PD groups were evaluated using 2-tailed Student’s t tests or χ² tests. For each LDDR area, regional ΔHC values were computed for the LID, NLID, and healthy control subjects and compared across groups using 1-way ANOVA with post-hoc Bonferroni tests as appropriate. Group × condition interaction effects in the CBF data were assessed for each VOI using 2 × 2 repeated-measures ANOVA with post-hoc Bonferroni tests. The relationship between ΔDA and ΔHC in regions with significant dissociation effects was assessed by computing Pearson product-moment correlation. Parallel statistical analyses were performed on ΔHC values measured in the clusters with significant group × condition interaction effects identified in the exploratory voxel-wise searches described above.

All statistical analyses were performed in SAS 9.3, and the results were considered significant at P < 0.05.

Study approval. Ethical approval for the studies was obtained from the Institutional Review Board of Northwell Health. Written consent was obtained from each subject after detailed explanation of the procedures.

Author contributions
DE designed the research; VAJ, KAS, MN, YYC, DM, AN, DN, NC, AF, and VD performed the research; VAJ, CCT, YM, SP, and DE analyzed the data; and VAJ, KAS, and DE wrote the paper.

Acknowledgments
This work was supported by the National Institute of Neurological Disorders and Stroke Morris K. Udall Center of Excellence for Parkinson’s Disease Research at the Feinstein Institute for Medical Research (P50 NS071675 to DE). The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institute of Neurological Disorders and Stroke or the National Institutes of Health. The sponsor did not play a role in study design; collection, analysis, and interpretation of data; writing of the report; or in the decision to submit the paper for publication. VAJ is the recipient of a fellowship award from the Fonds de Recherche en Santé du Québec. KAS is the recipient of the Leopoldina Fellowship Programme of the German National Academy of Sciences Leopoldina (LDS 2016-08). The authors thank Toni Fitzpatrick and Michael Small for their assistance in preparing the manuscript for publication. Special thanks to Thomas Chaly for valuable radiochemistry support and to David Bjelke, Claude Margouleff, and Limei Zhuo for technical assistance.

Address correspondence to: David Eidelberg, 350 Community Drive, Manhasset, New York 11030, USA. Phone: 516.562.2498; Email: deidelbe@northwell.edu.

10. Rocher AB, Chapon F, Bliaizot X, Baron JC, Chavoix C. Resting-state brain glucose utilization as measured by PET is directly


