Case Report/Case Series

Clinical Correlations With Lewy Body Pathology in *LRRK2*-Related Parkinson Disease

Lorraine V. Kalia, MD, PhD; Anthony E. Lang, MD; Lili-Naz Hazrati, MD, PhD; Shinsuke Fujioka, MD; Zbigniew K. Wszolek, MD; Dennis W. Dickson, MD; Owen A. Ross, PhD; Vivianna M. Van Deerlin, MD, PhD; John Q. Trojanowski, MD, PhD; Howard I. Hurtig, MD; Roy N. Alcalay, MD; Karen S. Marder, MD, MPH; Lorraine N. Clark, PhD; Carles Gaig, MD; Eduardo Tolosa, MD, PhD; Javier Ruiz-Martínez, MD, PhD; Jose F. Marti-Masso, MD, PhD; Isidre Ferrer, MD, PhD; Adolfo López de Munain, MD, PhD; Samuel M. Goldman, MD, MPH; Birgitt Schüle, MD; J. William Langston, MD; Jan O. Aasly, MD; Maria T. Giordana, MD, PhD; Vincenzo Bonifati, MD, PhD; Andreas Puschmann, MD, PhD; Margherita Canesi, MD; Gianni Pezzoli, MD; Andre Maues De Paula, MD; Kazuko Hasegawa, MD; Charles Duyckaerts, MD, PhD; Alexis Brice, MD, PhD; A. Jon Stoessl, MD; Connie Marras, MD, PhD

IMPORTANCE Mutations in leucine-rich repeat kinase 2 (*LRRK2*) are the most common cause of genetic Parkinson disease (PD) known to date. The clinical features of manifesting *LRRK2* mutation carriers are generally indistinguishable from those of patients with sporadic PD. However, some PD cases associated with *LRRK2* mutations lack Lewy bodies (LBs), a neuropathological hallmark of PD. We investigated whether the presence or absence of LBs correlates with different clinical features in *LRRK2*-related PD.

OBSERVATIONS We describe genetic, clinical, and neuropathological findings of 37 cases of *LRRK2*-related PD including 33 published and 4 unpublished cases through October 2013. Among the different mutations, the *LRRK2* p.G2019S mutation was most frequently associated with LB pathology. Nonmotor features of cognitive impairment/dementia, anxiety, and orthostatic hypotension were correlated with the presence of LBs. In contrast, a primarily motor phenotype was associated with a lack of LBs.

CONCLUSIONS AND RELEVANCE To our knowledge, this is the first report of clinicopathological correlations in a series of *LRRK2*-related PD cases. Findings from this selected group of patients with PD demonstrated that parkinsonian motor features can occur in the absence of LBs. However, LB pathology in *LRRK2*-related PD may be a marker for a broader parkinsonian symptom complex including cognitive impairment.

JAMA Neurol. 2015;72(1):100-105. doi:10.1001/jamaneurol.2014.2704
Published online November 17, 2014.

Supplemental content at jamaneurology.com

Author Affiliations: Author affiliations are listed at the end of this article.

Corresponding Author: Lorraine V. Kalia, MD, PhD, Movement Disorders Centre, Toronto Western Hospital, 399 Bathurst St, McL 7, Toronto, ON M5T 2S8, Canada (lorraine.kalia@utoronto.ca).

Mutations in leucine-rich repeat kinase 2 (*LRRK2*) are the most frequent cause of genetic Parkinson disease (PD), accounting for at least 4% of autosomal dominant forms of familial PD and 1% of sporadic PD worldwide.[1] The *LRRK2* gene encodes a large multidomain protein that includes an enzymatically active central region surrounded by a series of putative protein-protein interaction domains.[2] Disease-causing mutations are concentrated within the central region of the protein, which contains an ROC GTPase domain, a COR sequence, and a serine/threonine kinase domain. Thus far, at least 8 mutations (p.N1437H, p.R1441C/G/H, p.Y1699C, p.G2019S, p.I2020T, and possibly p.I1371V) are considered to be pathogenic. p.G2019S is the most frequent mutation but penetrance of p.G2019S and other pathogenic *LRRK2* mutations is incomplete.[3-5]

The clinical presentation of manifesting *LRRK2* mutation carriers tends to be indistinguishable from that of sporadic PD, with mean age at onset of approximately 60 years and appreciable response to levodopa.[6] Conversely, the neuropathological features can be atypical for PD and heterogeneous even within kindreds.[7] In particular, autopsy studies have revealed that Lewy bodies (LBs), which are large intraneuronal protein aggregates consisting primarily of α-synuclein,[8] are absent in a significant subset of cases. This was a surprising finding because LBs are neuropathological hallmarks of PD thought to be central to the neurodegenerative process and the clinical expression of PD and other synucleinopathies. Here we investigated the correlation of clinical features with LB pathology in *LRRK2*-related PD. This may provide insight into the relationship between α-synuclein pathology and specific features of the PD symptom complex.[9]

Methods

All published *LRRK2*-related autopsy cases up to October 2013 were identified by searching for English language articles in PubMed. The search terms *LRRK2*, *Lewy body/bodies*, *pathol-*

Table 1. Demographic and Genetic Features of all *LRRK2* Cases With and Without LB Pathology

Feature	With LBs (n = 17)	Without LBs (n = 20)	*P* Value
Male, % (no./No.)	23.5 (4/17)	40.0 (8/20)	.32
Race/ethnicity			
Non-Asian, % (no./No.)	92.9 (13/14)	57.9 (11/19)	.05
White non-Jewish, No.	10	10	
Ashkenazi Jewish, No.	3	1	
Asian, % (no./No.)	7.1 (1/14)	42.1 (8/19)	
Age at onset, mean (SD), y	56.0 (11.2)	61.0 (10.2)[a]	.17
Disease duration, mean (SD), y	19.2 (9.0)	16.2 (6.7)	.27
Age at death, mean (SD), y	75.2 (9.3)	77.2 (8.4)	.49
LRRK2 mutation			
p.G2019S, % (no./No.)	64.7 (11/17)	30.0 (6/20)	.05
Other, % (no./No.)	35.3 (6/17)	70.0 (14/20)	
p.I2020T, No.	1	8	
p.R1441C, No.	2	2	
p.R1441G, No.	0	2	
p.Y1699C, No.	1	2	
p.N1437H, No.	1	0	
p.I1371V, No.	1	0	

Abbreviations: LB, Lewy body; *LRRK2*, leucine-rich repeat kinase 2.

[a] Seventeen of 20 cases.

Table 2. Demographic Features of *LRRK2* p.G2019S Cases With and Without LB Pathology

Feature	With LBs (n = 11)	Without LBs (n = 6)	*P* Value
Male, % (no./No.)	36.4 (4/11)	50.0 (3/6)	.64
Race/ethnicity			
Ashkenazi Jewish, % (no./No.)	37.5 (3/8)	20.0 (1/5)	>.99
White non-Jewish, % (no./No.)	62.5 (5/8)	80.0 (4/5)	
Asian, % (no./No.)	0 (0/8)	0 (0/5)	
Age at onset, mean (SD), y	57.0 (12.8)	68.0 (7.5)	.07
Disease duration, mean (SD), y	21.1 (9.7)	13.5 (4.2)	.09
Age at death, mean (SD), y	78.1 (6.6)	81.5 (4.1)	.27
Family history of PD, % (no./No.)[a]	50.0 (5/10)	60.0 (3/5)	>.99

Abbreviations: LB, Lewy body; *LRRK2*, leucine-rich repeat kinase 2.

[a] At least 1 first-, second-, and/or third-degree relative with PD.

ogy/pathological, *neuropathology/neuropathological*, and/or *autopsy/autopsies* were used. Additional articles were found by searching the reference lists of identified articles and the authors' own files. Authors of published cases and directors of brain banks were contacted to identify unpublished cases. Clinical data were extracted from published articles. Additional data were obtained by requesting that investigators complete a clinical data form (eFigure in the Supplement) if the patient's clinic record was available. Neuropathological data were extracted from published articles and/or pathology reports when available. Cases were excluded if the associated *LRRK2* mutation was not one of the putative pathogenic mutations (previously mentioned), the patient did not have a clinical diagnosis of PD, or there was minimal or no available clinical and/or pathological information. Epi Info 7 from the Centers for Disease Control and Prevention was used for data analysis (www.cdc.gov/epiinfo/). Categorical variables were compared using the Fisher exact test. Continuous variables were compared using the *t* test. Logistic regression was performed to adjust for disease duration and age at death. Adjustment for Alzheimer disease–related pathology was made, where indicated, using Braak neurofibrillary tangle stage, which was estimated from the available data and dichotomized (≤stage III and ≥ stage IV). When necessary, a flattening constant of 1 was added to each cell to allow an odds ratio to be calculated. No imputation was made for missing data; patients missing values on an outcome were not included in the analysis for that outcome. Because this was an exploratory study, no adjustments were made for multiple comparisons. Separate analyses were also performed for p.G2019S-only cases. The study was approved by the ethics board of the University Health Network, Toronto, Ontario, Canada.

Results

Fifty-nine autopsy cases with *LRRK2* variants were identified: 54 published and 5 unpublished cases. Twenty-two cases were excluded from the analysis: 3 with nonpathogenic variants; 2 nonmanifesting *LRRK2* mutation carriers without a clinical diagnosis of PD; and 17 with insufficient clinical and/or pathological data (eTable 1 in the Supplement). No cases were excluded for neurological disease other than PD. Thirty-seven *LRRK2*-related PD cases were included: 33 published and 4 unpublished cases (17 with LBs and 20 without LBs) (eTable 2 in the Supplement). Neuronal loss within the substantia nigra was reported for all of these cases except for 2, in which these data were not provided. There were very limited data on neuronal loss within other brain regions. The demographic and genetic features of all included cases are summarized in **Table 1**. All cases with a p.I2020T mutation were of Japanese ethnicity. Cases with or without LBs were similar with respect to sex, disease duration, and age at death. Cases with LBs were more likely to have a p.G2019S mutation. The demographic features of p.G2019S cases (11 with LBs and 6 without LBs) are summarized in **Table 2**.

Table 3 provides a summary of the frequency of clinical features in *LRRK2* cases with or without LBs. Tremor was the most common presenting symptom for *LRRK2* patients regardless of the presence of LBs (65% for both groups). Cardinal motor symptoms, atypical features, levodopa responsiveness, and motor complications (see eFigure in the Supplement for details) occurred with similar frequency in both groups for all *LRRK2* cases and for the subset of p.G2019S cases. Certain nonmotor features (documented on history and/or examination) were more frequent among *LRRK2* cases with LBs. After adjusting for disease duration and age at death, cognitive impairment/dementia, anxiety, and orthostatic hypotension were associated with the presence of LBs (**Table 4**). Cognitive impairment/dementia and

Table 3. Frequency of Clinical Features With or Without LB Pathology[a]

Feature	All *LRRK2* Cases (N = 37)			*LRRK2* p.G2019S Cases (n = 17)		
	With LBs (n = 17)	Without LBs (n = 20)	*P* Value	With LBs (n = 11)	Without LBs (n = 6)	*P* Value
Motor features, % (no./No.)						
Bradykinesia	100 (17/17)	100 (18/18)	>.99	100 (11/11)	100 (5/5)	>.99
Rigidity	100 (17/17)	100 (15/15)	>.99	100 (11/11)	100 (6/6)	>.99
Tremor	94 (16/17)	94 (16/17)	>.99	91 (10/11)	100 (6/6)	>.99
Postural instability	100 (16/16)	92 (12/13)	.45	100 (11/11)	80 (4/5)	.31
Atypical features	17 (2/12)[b,c]	33 (3/9)[d]	.61	11 (1/9)[c]	0 (0/3)	>.99
Nonmotor features, % (no./No.)						
Cognitive impairment/dementia	**67 (10/15)**	**20 (4/20)**	**.01**	**82 (9/11)**	**17 (1/6)**	**.03**
Depression	79 (11/14)	38 (3/8)	.08	89 (8/9)	67 (2/3)	.45
Anxiety	**82 (9/11)**	**0 (0/7)**	**.002**	**100 (8/8)**	**0 (0/3)**	**.006**
Orthostatic hypotension	**50 (6/12)**	**0 (0/13)**	**.005**	63 (5/8)	0 (0/3)	.18
Urinary symptoms	40 (4/10)	25 (3/12)	.65	57 (4/7)	0 (0/2)	.44
Constipation	78 (7/9)	38 (5/13)	.10	100 (6/6)	100 (2/2)	>.99
Levodopa treatment, % (no./No.)						
Positive response[e]	80 (8/10)[f]	86 (12/14)[g]	>.99	71 (5/7)	60 (3/5)[g]	>.99
Fluctuations	67 (10/15)	80 (12/15)	.68	64 (7/11)	67 (4/6)	>.99
Dyskinesia	73 (11/15)	62 (8/13)	.69	80 (8/10)	50 (3/6)	.30
Maximum levodopa dose, mean (SD), mg	798 (431)	836 (504)	.85	741 (395)	840 (391)	.67
No. of cases	10	11		8	5	

Abbreviations: LB, Lewy body; *LRRK2*, leucine-rich repeat kinase 2.

[a] The results for the features in bold are statistically significant.

[b] One patient had supranuclear gaze palsy.

[c] One patient had upper motor neuron signs and myoclonus.

[d] One patient had upper motor neuron signs, 1 patient had supranuclear gaze palsy and upper motor neuron signs, and 1 patient had amyotrophy.

[e] Percentage of patients with moderate to marked levodopa response.

[f] One patient did not have a trial of levodopa.

[g] One patient could not tolerate levodopa.

anxiety were also associated with the presence of LBs within the subgroup of cases with the p.G2019S mutation. The association between cognitive impairment/dementia and the presence of LBs was maintained after adjustment for the degree of Alzheimer disease–related pathology (odds ratio, 8.14; 95% CI, 1.46-45.47; $P = .02$ for all *LRRK2* cases and odds ratio, 76.03; 95% CI, 1.07-5414.76; $P = .047$ for only p.G2019S cases).

Discussion

To our knowledge, this study is the first report of clinicopathological correlations in a series of *LRRK2*-related PD cases. We found that a primarily motor phenotype was associated with an absence of LBs. Parkinsonism (ie, bradykinesia plus rigidity, tremor, and/or postural instability) occurring independently of LB pathology has also been observed in the context of mutations in *PARK2*, which encodes parkin, where most autopsy reports describe an absence of LBs.[10] Conversely, LBs have been detected in the brains of people without the motor features of PD, an entity termed *incidental LB disease*. Our findings are consistent with these observations that LBs are neither necessary nor sufficient for the clinical expression of parkinsonism. Yet, there is strong evidence in experimental mouse models of PD that accumulation of α-synuclein aggregates in the substantia nigra pars compacta is associated with the death of dopaminergic neurons that harbor these aggregates with concomitant loss of tyrosine hydroxylase and dopamine metabolites in the dorsal striatum.[11] There is similar evidence linking α-synuclein aggregates in hippocampus to hippocampal neuron loss and cognitive impairment.[12] It is proposed that the neuropathological correlate of parkinsonian motor features is neuronal loss in the ventrolateral tier of the substantia nigra pars compacta.[8] However, loss of nigral neurons is also not specific for a diagnosis of PD because it occurs in many other neurodegenerative disorders with prominent parkinsonism such as progressive supranuclear palsy and multiple system atrophy.

The expression of nonmotor features in this series of *LRRK2*-related PD cases was found to be related to the presence of LBs. In particular, cognitive impairment/dementia, anxiety, and orthostatic hypotension were more likely to occur at some point during the disease course in patients who were found to have LBs at autopsy. Many nonmotor features tend to occur with longer disease duration and/or older age[13] but we did not find that these potential confounders accounted for the differences observed between those with or without LBs. Evidence for an association between Lewy pathology and nonmotor symptoms has been previously demonstrated for cognitive impairment in PD. In particular, several studies have demonstrated a

Table 4. Clinical Correlates of LB Pathology in *LRRK2*-Associated Parkinson Disease[a,b]

	All *LRRK2* Cases (N = 37)		*LRRK2* p.G2019S Cases (n = 17)	
Feature	OR (95% CI)	*P* Value	OR (95% CI)	*P* Value
Motor features				
Bradykinesia	0.95 (0.05-17.97)	.97	2.49 (0.08-80.81)	.61
Rigidity	1.22 (0.06-26.80)	.90	1.94 (0.07-53.77)	.69
Tremor	1.03 (0.04-26.52)	.99	0.60 (0.04-9.19)	.71
Postural instability	2.22 (0.16-30.44)	.55	4.55 (0.23-89.65)	.32
Atypical features	0.54 (0.05-6.19)	.62	1.38 (0.08-25.39)	.83
Nonmotor features				
Cognitive impairment/dementia	**9.74 (1.80-52.60)**	**.008**	**85.64 (1.52-4817.27)**	**.03**
Depression	3.06 (0.36-26.07)	.31	3.33 (0.06-184.51)	.56
Anxiety	**17.87 (1.37-233.28)**	**.03**	**24.69 (1.14-536.51)**	**.04**
Orthostatic hypotension	**12.03 (1.17-123.93)**	**.04**	4.35 (0.31-61.10)	.28
Urinary symptoms	2.25 (0.29-17.46)	.44	6.82 (0.36-130.83)	.20
Constipation	14.49 (0.78-267.71)	.07	1.95 (0.06-68.51)	.71
Levodopa treatment				
Positive response	0.11 (0.01-2.42)	.16	0.10 (0-3.21)	.19
Fluctuations	0.10 (0.01-1.53)	.10	0.14 (0.01-3.31)	.22
Dyskinesia	0.31 (0.02-4.72)	.40	0.92 (0.05-16.14)	.95

Abbreviations: LB, Lewy body; *LRRK2*, leucine-rich repeat kinase 2; OR, odds ratio.

[a] Adjusted for disease duration and age at death.

[b] The results for the features in bold are statistically significant.

strong correlation between dementia and severity of cortical Lewy pathology.[14-16]

Based on our findings, we hypothesize that *LRRK2*-related PD with LBs is associated with more extensive neurodegeneration whereas neuronal loss may be more restricted (eg, to the substantia nigra pars compacta) in cases lacking LBs. This would be similar to parkin-related PD in which there is frequently an absence of LBs, restricted neurodegeneration, and a relative lack of nonmotor features.[10] In patients with sporadic PD, cortical Lewy pathology correlates with dementia but Alzheimer disease plaques and tangles also contribute to their cognitive impairment.[16,17] It is possible that aggregates of proteins other than α-synuclein are contributors to the clinical expression of *LRRK2*-related PD. Standardized neuropathological assessments of a series of *LRRK2* autopsy cases, including semiquantitative measures of neuronal loss and examination of various protein aggregates in brain stem, subcortical, and cortical structures, are needed to further interrogate correlations with specific motor and nonmotor symptoms in *LRRK2*-related PD.

Prior reports have highlighted the occurrence of atypical neuropathological findings at autopsy for some manifesting *LRRK2* mutation carriers including pathology resembling progressive supranuclear palsy, multiple system atrophy, or frontotemporal lobar degeneration with ubiquitin-positive inclusions, presence of TDP-43 inclusions, and/or lack of LB pathology (eTable 2). Our assessment was limited to clinical correlations with LBs because this was the only neuropathological feature available for all cases. Additional details—such as the presence of α-synuclein immunoreactive inclusions in neuronal processes (eg, Lewy neurites, dotlike structures, and axonal spheroids), degree of neuronal loss, involvement of extranigral structures, immunostaining results for other protein inclusions, and the distribution of these features—were unavailable for many cases so analysis of these other features could not be carried out here. Furthermore, there is a lack of standard operating procedures for the neuropathological diagnosis of PD[8] and methodological differences (eg, areas sampled, immunostaining performed, and types of antibodies used) among the different centers may have produced variable results. Ongoing and future efforts to standardize autopsy collection, handling, and reporting for *LRRK2*-related PD cases will help to provide data for more detailed clinicopathological correlations.

The *LRRK2* autopsy cases used in this study were identified primarily from published reports; therefore, there is the potential for ascertainment bias. Furthermore, the cases came from differing sources (eg, individual cases, large kindreds, and brain banks). The clinical data acquired in the study were based on retrospective reports by the patients, caregivers, and/or treating physician. The nature of this study precluded standardized clinical assessments, which is a significant limitation. An additional limitation includes the potential for false-positive findings due to multiple comparisons. Regardless, our observations raise the hypothesis that LB pathology may be the underlying basis for cognitive dysfunction in *LRRK2* disease while at the same time being a marker for a broader parkinsonian symptom complex in *LRRK2*-related PD. This can be tested in future prospective cohort studies of patients with *LRRK2* mutations.

An important unresolved question is: why are LBs absent in a subset of patients with *LRRK2*-related PD? The large number of cases reported from various centers demonstrates that LB-negative *LRRK2*-related PD is not an anomalous finding. Genotype cannot account for this finding because the subset of patients without LBs is not represented by 1 specific *LRRK2* mutation. The possibility that *LRRK2*-related PD represents a distinct disease from sporadic PD and thus can present with non-LB pathology is unlikely based on the significant clinical similarities between PD associated with *LRRK2* mutations and

sporadic PD,[6] evidence from genome-wide association studies demonstrating that *LRRK2* polymorphisms are genetic risk factors for sporadic PD,[18] and experimental findings that implicate the LRRK2 protein in molecular pathways underlying PD pathogenesis.[2] While our study did not explain why LBs are sometimes absent in *LRRK2*-related PD, it contributes to the accumulating evidence that LBs alone cannot explain the pathogenesis of PD but other forms of α-synuclein may also play important roles.[19] Indeed, small soluble aggregates of α-synuclein have been isolated from the cortex of a patient with G2019S *LRRK2* PD without LBs.[20] Our study also supports the ongoing effort to reevaluate the pathological criteria used to define PD, in particular, deemphasizing LBs as a core feature.[21]

Conclusions

Lewy body pathology is not present in all patients with *LRRK2*-related PD. The mutation p.G2019S is more frequently associated with LB pathology compared with other *LRRK2* mutations. The classic parkinsonian motor symptoms can occur without LBs, and a primarily motor phenotype appears to be associated with an absence of LBs. The expression of certain nonmotor features, particularly cognitive impairment, anxiety, and orthostatic hypotension, is related to the presence of LBs. Thus, LB pathology in *LRRK2*-related PD may be a marker for a broader parkinsonian symptom complex.

ARTICLE INFORMATION

Accepted for Publication: July 31, 2014.

Published Online: November 17, 2014. doi:10.1001/jamaneurol.2014.2704.

Author Affiliations: The Edmond J. Safra Program in Parkinson's Disease, University Health Network, Division of Neurology, Department of Medicine, University of Toronto, Toronto, Ontario, Canada (Kalia, Lang, Marras); Department of Laboratory Medicine and Pathobiology, University of Toronto, Toronto, Ontario, Canada (Hazrati); Mayo Clinic, Jacksonville, Florida (Fujioka, Wszolek, Dickson, Ross); University of Pennsylvania, Philadelphia (Van Deerlin, Trojanowski, Hurtig); Columbia University, New York, New York (Alcalay, Marder, Clark); Hospital Clínic de Barcelona, Universitat de Barcelona, IDIBAPS, Centro de Investigación Biomédica en Red sobre Enfermedades Neurodegenerativas (CIBERNED), Barcelona, Catalonia, Spain (Gaig, Tolosa); Hospital Universitario Donostia, CIBERNED, San Sebastián, Spain (Ruiz-Martínez, Marti-Masso, López de Munain); Bellvitge University Hospital, L' Hospitalet de Llobregat, Barcelona, Spain (Ferrer); Veterans Affairs Medical Center, San Francisco, California (Goldman); The Parkinson's Institute, Sunnyvale, California (Schüle, Langston); St Olavs Hospital, Trondheim, Norway (Aasly); University of Turin, Turin, Italy (Giordana); Erasmus MC, Rotterdam, the Netherlands (Bonifati); Skåne University Hospital and Lund University, Lund, Sweden (Puschmann); Parkinson Institute, Istituti Clinici di Perfezionamento, Milan, Italy (Canesi, Pezzoli); Centre Hospitalier Universitaire La Timone, Marseille, France (Maues De Paula); Sagamihara National Hospital, Kanagawa, Japan (Hasegawa); Sorbonne Université, Pierre and Marie Curie University, Institut du Cerveau et de la Moelle Epinière, Institut National de la Santé et de la Recherche Médicale, Centre national de la recherche scientique, Paris, France (Duyckaerts, Brice); University of British Columbia, Vancouver, British Columbia, Canada (Stoessl).

Author Contributions: Drs Kalia and Marras had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis.
Study concept and design: Kalia, Lang, Hazrati, Marras.
Acquisition, analysis, or interpretation of data: All authors.
Drafting of the manuscript: Kalia.
Critical revision of the manuscript for important intellectual content: All authors.
Statistical analysis: Kalia.
Obtained funding: Kalia, Hazrati, Wszolek, Ross, Van Deerlin, Trojanowski, Alcalay, Clark, Gaig, Tolosa, Langston, Puschmann, Pezzoli, Brice.
Administrative, technical, or material support: Wszolek, Dickson, Clark, Ruiz-Martínez, Ferrer, Goldman, Schüle, Aasly, Giordana, Bonifati, Hasegawa.
Study supervision: Lang, Marti-Masso, López de Munain, Marras.

Conflict of Interest Disclosures: Dr Kalia has received educational support from Allergan. Dr Lang has served as an advisor for Abbott, Abbvie, Allon Therapeutics, Avanir Pharmaceuticals, Biogen Idec, Boerhinger-Ingelheim, Ceregene, Medtronic, Merck, Novartis, NeuroPhage Pharmaceuticals, Teva Pharmaceuticals, and UCB; has received publishing royalties from Saunders, Wiley-Blackwell, Johns Hopkins Press, and Cambridge University Press; and has served as an expert witness in cases related to the welding industry. Mayo Clinic and Dr Wszolek have a financial interest in technologies titled, "Identification of Mutations in *PARK8*, a Locus for Familial Parkinson's Disease" and "Identification of a Novel *LRRK2* Mutation, 6055G>A (G2019S), Linked to Autosomal Dominant Parkinsonism in Families from Several European Populations." Those technologies have been licensed to commercial entities and Dr Wszolek has received royalties through Mayo Clinic in accordance with its royalty-sharing policies. Dr Trojanowski has received funding for travel and honoraria from Takeda Pharmaceutical Co Ltd; has received speaker honoraria from Pfizer Inc; and serves as an associate editor of *Alzheimer's & Dementia*. Dr Trojanowski may accrue revenue on patents regarding a modified avidin-biotin technique; method of stabilizing microtubules to treat Alzheimer's disease; method of detecting abnormally phosphorylated tau; method of screening for Alzheimer's disease or disease associated with the accumulation of paired helical filaments; compositions and methods for producing and using homogeneous neuronal cell transplants; rat comprising straight filaments in its brain; compositions and methods for producing and using homogeneous neuronal cell transplants to treat neurodegenerative disorders and brain and spinal cord injuries; diagnostic methods for Alzheimer's disease by detection of multiple MRNAs; methods and compositions for determining lipid peroxidation levels in oxidant stress syndromes and diseases; compositions and methods for producing and using homogenous neuronal cell transplants; method of identifying, diagnosing, and treating α-synuclein–positive neurodegenerative disorders; mutation-specific functional impairments in distinct tau isoforms of hereditary frontotemporal dementia and parkinsonism linked to chromosome-17: genotype predicts phenotype; microtubule-stabilizing therapies for neurodegenerative disorders; and treatment of Alzheimer's and related diseases with an antibody. Dr Tolosa has served as a consultant to Novartis, Teva Pharmaceuticals, Boerhinger-Ingelheim, UCB, Lundbeck, and Abbvie. Dr Langston has received funding from Teva Pharmaceuticals. Dr Hasegawa has received honoraria from Boerhinger-Ingelheim, GlaxoSmithKline, Kyowa Hakko Kirin Co, Novartis, Otsuka Pharmaceutical Co, and Dainippon Sumitomo Pharm Co. Dr Brice has received honoraria from Lundbeck. Dr Stoessl has served as an advisor for Abbott, Abbvie, Biogen Idec, Medgenesis, and UCB and has received honoraria from Teva Pharmaceuticals. Dr Marras has received honoraria for teaching from EMD Serono. No other disclosures were reported.

Funding/Support: Dr Kalia is supported by a Canadian Health Institutes of Research (CIHR) Clinician-Scientist Award. Dr Lang holds the Jack Clark Chair in Parkinson's Disease Research; has received grants from Brain Canada, CIHR, Edmond J. Safra Philanthropic Foundation, Michael J. Fox Foundation (MJFF), National Parkinson Foundation (NPF), Parkinson Society Canada (PSC), Tourette Syndrome Association, and W. Garfield Weston Foundation. Dr Fujioka was partially supported by a gift from Carl Edward Bolch Jr and Susan Bass Bolch. Dr Wszolek receives support from the National Institutes of Health (NIH)/National Institute of Neurological Disorders and Stroke (NINDS) P50 NS072187, Mayo Clinic Center for Regenerative Medicine, MJFF, and a gift from Carl Edward Bolch Jr and Susan Bass Bolch. Dr Ross is supported by NIH/NINDS P50 NS072187 and NIH/NINDS R01 NS078086. Drs Van Deerlin and Hurtig receive support from NIH/NINDS P50 NS053488. Dr Trojanowski receives research support from the NIH (National Institute on Aging [NIA] grants P01 AG 09215-20 [principal investigator (PI)], NIA P30 AG 10124-18 [PI], NIA PO1 AG 17586-10 [project 4 leader], NIA 1PO1 AG-19724-07 [core C leader], NIA 1 U01 AG 024904-05 [co-PI Biomarker Core Laboratory], NINDS P50 NS053488-02 [PI], NIA UO1 AG029213-01 [co-I], RC2NS069368 [PI], RC1AG035427 [PI], and NIA P30AG036468 [PI]) and from the Marian S. Ware Alzheimer Program. Dr Trojanowski is also the William Maul Measey-Truman G. Schnabel Jr, MD, Professor of Geriatric

Medicine and Gerontology. Dr Alcalay receives research support from the NIH (K02 NS080915), Parkinson's Disease Foundation (PDF), Smart Foundation, and MJFF. Dr Marder receives research support from the NIH (NS036630 [PI], 1UL1 RR024156-01 [director PCIR], PO412196- G [co-I], and PO412196-G [co-I]); has received compensation for participating on the steering committee for U01 NS052592 and from the PDF, Huntington's Disease Society of America, Parkinson Study Group, Cure Huntington's Disease Initiative, and MJFF. Dr Clark is supported by the PDF, MJFF, and NIH (grants NINDS R01 NS060113, NINDS R01 NS073872, NIA P50 AG 008702, NINDS NS36630, and P50 NS038370). Dr Tolosa has received research grants from Instituto de Salud Carlos III, Fondo de Investigaciones Sanitarias de la Seguridad Social, and MJFF. Dr Goldman has received grants from the National Institute for Occupational Safety and Health, Department of Defense, and MJFF. Dr Langston receives support from the NIH, Department of Defense, California Institute for Regenerative Medicine, and MJFF. Dr Aasly has received grants from the Norwegian Parkinson Foundation, Norwegian Research Council, and MJFF. Dr Bonifati has received research grants from the Netherlands Organization for Scientific Research (NWO-VIDI grant) and Stichting Parkinson Fonds (the Netherlands). Dr Puschmann is supported by governmental funding for clinical research within the Swedish National Health Services (ALF-YF), Swedish Parkinson Foundation (Parkinsonfonden), and Swedish Parkinson Academy (Parkinsonakademien). Drs Duyckaerts and Brice are supported by the program "Investissements d'avenir" ANR-10-IAIHU-06. Dr Brice has received honoraria from the Wolfson Foundation and research support from the French Agency for Research and European Union. Dr Stoessl has received grants from CIHR, MJFF, NPF, and Pacific Alzheimer Research Foundation and philanthropic research support from the Cundill Foundation and Pacific Parkinson's Research Institute and is supported by the Canada Research Chairs program. Dr Marras has received grants from the MJFF, CIHR, NPF, and PSC.

Role of the Funder/Sponsor: The funders had no role in the design and conduct of the study; collection, management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; and decision to submit the manuscript for publication.

Additional Contributions: We thank Boris Dufournet (Centre Hospitalier Universitaire La Timone, Marseille, France) for assistance with data acquisition. He received no compensation from a funding sponsor for his contribution.

REFERENCES

1. Healy DG, Falchi M, O'Sullivan SS, et al; International LRRK2 Consortium. Phenotype, genotype, and worldwide genetic penetrance of LRRK2-associated Parkinson's disease: a case-control study. *Lancet Neurol*. 2008;7(7):583-590.

2. Cookson MR. The role of leucine-rich repeat kinase 2 (LRRK2) in Parkinson's disease. *Nat Rev Neurosci*. 2010;11(12):791-797.

3. Funayama M, Hasegawa K, Kowa H, Saito M, Tsuji S, Obata F. A new locus for Parkinson's disease (PARK8) maps to chromosome 12p11.2-q13.1. *Ann Neurol*. 2002;51(3):296-301.

4. Ruiz-Martínez J, Gorostidi A, Ibañez B, et al. Penetrance in Parkinson's disease related to the LRRK2 R1441G mutation in the Basque country (Spain). *Mov Disord*. 2010;25(14):2340-2345.

5. Goldwurm S, Tunesi S, Tesei S, et al. Kin-cohort analysis of LRRK2-G2019S penetrance in Parkinson's disease. *Mov Disord*. 2011;26(11):2144-2145.

6. Marras C, Schüle B, Munhoz RP, et al. Phenotype in parkinsonian and nonparkinsonian LRRK2 G2019S mutation carriers [published correction appears in *Neurology*. 2011;77(15):1501]. *Neurology*. 2011;77(4):325-333.

7. Poulopoulos M, Levy OA, Alcalay RN. The neuropathology of genetic Parkinson's disease. *Mov Disord*. 2012;27(7):831-842.

8. Dickson DW, Braak H, Duda JE, et al. Neuropathological assessment of Parkinson's disease: refining the diagnostic criteria. *Lancet Neurol*. 2009;8(12):1150-1157.

9. Langston JW. The Parkinson's complex: parkinsonism is just the tip of the iceberg. *Ann Neurol*. 2006;59(4):591-596.

10. Doherty KM, Silveira-Moriyama L, Parkkinen L, et al. Parkin disease: a clinicopathologic entity? *JAMA Neurol*. 2013;70(5):571-579.

11. Luk KC, Kehm V, Carroll J, et al. Pathological α-synuclein transmission initiates Parkinson-like neurodegeneration in nontransgenic mice. *Science*. 2012;338(6109):949-953.

12. Lim Y, Kehm VM, Lee EB, et al. α-Syn suppression reverses synaptic and memory defects in a mouse model of dementia with Lewy bodies. *J Neurosci*. 2011;31(27):10076-10087.

13. Hely MA, Morris JGL, Reid WGJ, Trafficante R. Sydney Multicenter Study of Parkinson's Disease: non-L-dopa-responsive problems dominate at 15 years. *Mov Disord*. 2005;20(2):190-199.

14. Selikhova M, Williams DR, Kempster PA, Holton JL, Revesz T, Lees AJ. A clinico-pathological study of subtypes in Parkinson's disease. *Brain*. 2009;132(pt 11):2947-2957.

15. Kempster PA, O'Sullivan SS, Holton JL, Revesz T, Lees AJ. Relationships between age and late progression of Parkinson's disease: a clinico-pathological study. *Brain*. 2010;133(pt 6):1755-1762.

16. Irwin DJ, White MT, Toledo JB, et al. Neuropathologic substrates of Parkinson disease dementia. *Ann Neurol*. 2012;72(4):587-598.

17. Irwin DJ, Lee VM-Y, Trojanowski JQ. Parkinson's disease dementia: convergence of α-synuclein, tau and amyloid-β pathologies. *Nat Rev Neurosci*. 2013;14(9):626-636.

18. Lill CM, Roehr JT, McQueen MB, et al; 23andMe Genetic Epidemiology of Parkinson's Disease Consortium; International Parkinson's Disease Genomics Consortium; Parkinson's Disease GWAS Consortium; Wellcome Trust Case Control Consortium 2. Comprehensive research synopsis and systematic meta-analyses in Parkinson's disease genetics: the PDGene database. *PLoS Genet*. 2012;8(3):e1002548.

19. Kalia LV, Kalia SK, McLean PJ, Lozano AM, Lang AE. α-Synuclein oligomers and clinical implications for Parkinson disease. *Ann Neurol*. 2013;73(2):155-169.

20. Gomez A, Ferrer I. Involvement of the cerebral cortex in Parkinson disease linked with G2019S LRRK2 mutation without cognitive impairment. *Acta Neuropathol*. 2010;120(2):155-167.

21. Berg D, Postuma RB, Bloem B, et al. Time to redefine PD? introductory statement of the MDS Task Force on the definition of Parkinson's disease. *Mov Disord*. 2014;29(4):454-462.