

Analysis of common and rare *VPS13C* variants in late-onset Parkinson disease

Uladzislau Rudakou, BSc, Jennifer A. Ruskey, MSc, Lynne Krohn, MSc, Sandra B. Laurent, BSc, Dan Spiegelman, MSc, Lior Greenbaum, MD, PhD, Gilad Yahalom, MD, Alex Desautels, MD, PhD, Jacques Y. Montplaisir, MD, PhD, Stanley Fahn, MD, Cheryl H. Waters, MD, Oren Levy, MD, PhD, Caitlin M. Kehoe, MA, Sushma Narayan, MS, Yves Dauvilliers, MD, PhD, Nicolas Dupré, MD, FRCP, Sharon Hassin-Baer, MD, Roy N. Alcalay, MD, MS, Guy A. Rouleau, MD, PhD, FRCPC, FRSC, Edward A. Fon, MD, FRCPC, and Ziv Gan-Or, MD, PhD

Correspondence
Dr. Gan-Or
ziv.gan-or@mcgill.ca

Neurol Genet 2020;6:e385. doi:10.1212/NXG.0000000000000385

Abstract

Objective

We aimed to study the role of coding *VPS13C* variants in a large cohort of patients with late-onset Parkinson disease (PD) (LOPD).

Methods

VPS13C and its untranslated regions were sequenced using targeted next-generation sequencing in 1,567 patients with PD and 1,667 controls from 3 cohorts. Association tests of rare potential homozygous and compound heterozygous variants and burden tests for rare heterozygous variants were performed. Common variants were analyzed using logistic regression adjusted for age and sex in each of the cohorts, followed by a meta-analysis.

Results

No biallelic carriers of rare *VPS13C* variants were found among patients, and 2 carriers of compound heterozygous variants were found in 2 controls. There was no statistically significant burden of rare (minor allele frequency [MAF] <1%) or very rare (MAF <0.1%) coding *VPS13C* variants in PD. A *VPS13C* haplotype including the p.R153H-p.I398I-p.I1132V-p.Q2376Q variants was nominally associated with a reduced risk for PD (meta-analysis of the tagging SNP p.I1132V [odds ratio = 0.48, 95% confidence interval = 0.28–0.82, $p = 0.0052$]). This haplotype was not in linkage disequilibrium with the known genome-wide association study top hit.

Conclusions

Our results do not support a role for rare heterozygous or biallelic *VPS13C* variants in LOPD. Additional genetic replication and functional studies are needed to examine the role of the haplotype identified here associated with reduced risk for PD.

From the Department of Human Genetics (U.R., L.K., G.A.R., Z.G.-O.), McGill University, Montréal; Montreal Neurological Institute (U.R., J.A.R., L.K., S.B.L., D.S., G.A.R., E.A.F.Z.G.-O.), McGill University; Department of Neurology and Neurosurgery (J.A.R., S.B.L., D.S., G.A.R., E.A.F., Z.G.-O.), McGill University, Montréal, Québec, Canada; The Danek Gertner Institute of Human Genetics, Sheba Medical Center (L.G.); The Joseph Sagol Neuroscience Center (L.G., S.H.-B.), Sheba Medical Center, Tel Hashomer, Ramat Gan; Sackler School of Medicine (L.G., G.Y., S.H.-B.), Tel-Aviv University; Department of Neurology (G.Y., S.H.-B.), Sheba Medical Center; Movement Disorders Institute (G.Y., S.H.-B.), Sheba Medical Center, Tel Hashomer, Ramat Gan, Israel; Centre d'Études Avancées en Médecine du Sommeil (A.D., J.Y.M.), Hôpital du Sacré-Cœur de Montréal; Department of Neurosciences (A.D.), Université de Montréal; Department of Psychiatry (J.Y.M.), Université de Montréal, Québec, Canada; Department of Neurology (S.F., C.H.W., O.L., C.M.K., S.N., R.N.A.), College of Physicians and Surgeons, Columbia University Medical Center, New York; Department of Neurology (Y.D.), National Reference Center for Narcolepsy, Sleep Unit, Gui-de-Chauliac Hospital, CHU Montpellier, University of Montpellier, Inserm, France; Division of Neurosciences (N.D.), CHU de Québec, Université Laval; Department of Medicine (N.D.), Faculty of Medicine, Université Laval, Québec City, Canada; and Taub Institute for Research on Alzheimer's Disease and the Aging Brain (R.N.A.), College of Physicians and Surgeons, Columbia University Medical Center, New York.

Go to [Neurology.org/NG](https://www.neurology.org/NG) for full disclosures. Funding information is provided at the end of the article.

The Article Processing Charge was funded by the authors.

This is an open access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License 4.0 (CC BY-NC-ND), which permits downloading and sharing the work provided it is properly cited. The work cannot be changed in any way or used commercially without permission from the journal.

Glossary

AJ = Ashkenazi Jewish; ANOVA = analysis of variance; CADD = Combined Annotation Dependent Depletion; CI = confidence interval; EOPD = early onset Parkinson disease; GATK = Genome Analysis Toolkit; GnomAD = Genome Aggregation Database; GQ = quality score; GWAS = genome-wide association study; LD = linkage disequilibrium; LOPD = late onset Parkinson disease; MAF = minor allele frequency; MIP = molecular inversion probe; OR = odds ratio; PD = Parkinson disease; QC = quality control.

The *VPS13C* gene is located within a risk locus for Parkinson disease (PD), reported in large genome-wide association studies (GWASs) of European population.^{1,2} The single nucleotide polymorphism (SNP) reported in the GWAS (rs2414739, chr15:hg19:g.61994134G>A) was also studied in several Asian populations and in Iranians, with conflicting results,^{3–7} possibly because of ethnicity-related differences.

Subsequently, homozygous and compound heterozygous *VPS13C* mutations were identified as a rare cause of early onset PD (EOPD) characterized by rapid progression and early cognitive dysfunction. It was demonstrated that *VPS13C* is partially localized at the mitochondrial membrane, and its silencing led to mitochondrial dysfunction and increased PINK1/Parkin-dependent mitophagy.⁸ A follow-up study in 80 patients with EOPD identified an additional patient with compound heterozygous mutations with similar clinical features to the previously reported patients.⁹ In another recent study, a homozygous deletion in *VPS13C* was reported to be the probable cause of early onset parkinsonism in 1 patient.¹⁰ Thus far, full sequencing studies of *VPS13C* have not been reported in late-onset PD (LOPD).

To further study the potential role of *VPS13C* variants in PD, we sequenced its coding and regulatory regions using targeted next-generation sequencing in 3 cohorts of PD (predominantly LOPD) and in controls. We examined the association of common, rare, and biallelic *VPS13C* variants on the risk for PD. We further tested whether any coding variant or variants in the untranslated regions of *VPS13C* are in linkage disequilibrium (LD) with the top *VPS13C*-associated GWAS hit to determine if any of these variants can explain the GWAS association of this locus.

Methods

Study population

Three cohorts, with a total of 1,567 unrelated patients with PD and 1,667 controls, were included in this study, detailed in table 1. The first cohort was composed of French and French Canadian participants recruited in Quebec (Canada) and in France. This cohort was previously genotyped using the GWAS OmniExpress array, the ethnicity was confirmed using principal component analysis, and the samples that were of different ethnicities were not included in this study. The second cohort was recruited in New York—Columbia

University and was previously described.¹¹ Most participants from New York are of European descent and 38% are Ashkenazi Jewish (AJ), 40% of patients with PD, and 35% of controls. This difference was not statistically significant, yet we adjusted for ethnicity when analyzing this cohort to avoid effects of ethnicity on the results. The third cohort was recruited in Israel (Sheba Medical Center), and all participants included in this study from the Israeli cohort are of full AJ origin (all 4 grandparents are full AJ). All patients were consecutively recruited through the clinics, and they represent the typical LOPD patient population with age at onset (AAO) of about 60 (table 1), as opposed to the studies published so far on *VPS13C* in EOPD. As detailed below, because of the differences in age and sex (table 1), statistical analysis was adjusted and included age and sex as covariates. To account for different ethnicities in the New York cohort, an ethnicity covariate was also introduced in this cohort (GWAS data were not available for this cohort; therefore, the reported ethnicity was used and not principal components). All 3 cohorts were sequenced in the same laboratory (McGill University), following the same protocol. All patients with PD were diagnosed by movement disorder specialists according to the UK Brain Bank criteria,¹² without excluding patients with family history of PD, because it is now known that there are familial cases of PD, so patients who reported family history of PD were included. However, it is important to emphasize that in the current study, only unrelated patients were included and there were no multiple cases from the same family.

Standard protocol approvals, registrations, and patient consents

The institutional review board (McGill University Health Center Research Ethics Board—MUHC REB) approved the study protocols (reference number IRB00010120). Informed consent was obtained from all individual participants before entering the study.

DNA extraction and *VPS13C* sequencing

DNA was extracted using a standard salting out protocol. The coding sequence and regulatory regions of *VPS13C* were targeted using molecular inversion probes (MIPs), which were designed as previously described.¹³ MIPs were selected based on their predicted coverage, quality, and overlap. All MIPs used to sequence *VPS13C* in the present study are included in table e-1, links.lww.com/NXG/A205. Targeted DNA capture and amplification was performed as previously described,¹⁴ and the full protocol is available on request. The

Table 1 Study population details

Sequenced				Analyzed						
				Cases			Controls			
N (cases)	N (controls)	Cohort	Min Depth of Coverage	N	Mean age (SD) y	% Male	N	Mean Age (SD) y	% Male	Genotyping call rate %
543	866	French/French Canadian	15× 50×	534	59.7 (11.4)	63.7	858	42.0 (13.6)	51.6	99.6
				498	59.8 (11.2)	63.5	785	42.3 (13.5)	52.0	99.2
533	270	New York	15× 50×	520	59.3 (11.8)	64.0	262	65.0 (9.8)	34.0	99.9
				502	59.3 (11.8)	64.1	245	65.4 (9.6)	32.7	99.5
491	531	Israel	15× 50×	482	60.6 (11.7)	61.8	488	33.9 (7.2)	57.8	99.3
				478	60.7 (11.7)	61.7	487	33.9 (7.2)	57.7	99.3

library was sequenced using an Illumina HiSeq 2,500 platform at the McGill University and Genome Quebec Innovation Centre. Reads were mapped to the human reference genome (hg19) with Burrows-Wheeler Aligner.¹⁵ Genome Analysis Toolkit (v3.8) was used for postalignment quality control (QC) and variant calling,¹⁶ and annotation variation was used for annotation.¹⁷ Data on the frequency of each *VPS13C* variant were extracted from the public database Genome Aggregation Database (GnomAD).¹⁸ Validation of the tagging variant p.I1132V was performed using Sanger sequencing, with the following primers: forward 5'-CCGGGAAGGTAATGACAAAA-3' and reverse 5'-CCCCTGATTGAAAAGTCACA-3'.

Quality control

During QC filtration using PLINK software v1.9,¹⁹ SNPs with genotyping rate lower than 90% were excluded. Genotyping rate cut-off for individuals was 90%, and individuals with a lower genotyping rate were excluded. SNPs that deviated from Hardy-Weinberg equilibrium set at $p = 0.001$ threshold were filtered out. Threshold for missingness difference between cases and controls was set at $p = 0.05$ and the filtration script adjusted it with Bonferroni correction. After these QC steps, cohort composition was as described in table 1. To be included in the analysis, minimum quality score (GQ) was set to 30. Rare variants (minor allele frequency [MAF] <0.01 or 0.001) had to have a minimal coverage of >50× to be included, and common variants had to have a minimal coverage of >15× to be included in the analysis.

Statistical analysis

The association between common *VPS13C* variants and PD was examined by using logistic regression models using PLINK v1.9, with the status (patient or control) as a dependent variable, age and sex as covariates in all cohorts, and AJ ancestry as an additional covariate in the New York cohort. To analyze rare variants (MAF <0.01) and very rare variants (MAF <0.001), an optimized sequence kernel association test (SKAT-O, R package) was performed.²⁰ In addition, we examined the burden of predicted pathogenic variants using SKAT-O with Combined Annotation Dependent Depletion (CADD) score of ≥ 12.37 representing the top 2% of potentially deleterious

variants. The effects of SNP genotypes on the AAO was tested using analysis of variance (ANOVA; in R software). Meta-analysis of common variants in the 3 cohorts was performed using metafor package in R software.²¹ LD in our data were examined by PLINK v1.9 and LD between discovered SNPs and the GWAS top hit rs2414739 was tested using LDlink application, selecting all non-Finish Europeans.²²

Data availability

Anonymized data are available on request by any qualified investigator.

Results

Rare *VPS13C* variants and homozygous or compound heterozygous *VPS13C* variants are not associated with LOPD

The average coverage of *VPS13C* with the MIPs was 94% of nucleotides covered at >10× and 90% covered at >50×. This coverage, while not ideal, is better than the whole exome sequencing coverage reported in the original study on *VPS13C* in PD and better than the whole exome and whole genome sequencing coverage of this specific gene in GnomAD (gnomad.broadinstitute.org/). There were no differences in coverage between the cohorts and between patients and controls. A total of 60 rare variants that are non-synonymous, stop variants, or potentially affect a splicing site were identified in the 3 cohorts and are detailed in table e-2, links.lww.com/NXG/A206.

To examine whether rare homozygous or compound heterozygous *VPS13C* variants may cause LOPD, and because patients with *VPS13C* biallelic mutations are very rare, we included only rare variants with allele frequency <0.001 in this analysis. Only 2 carriers of 2 heterozygous variants were identified, and both were controls (table e-3, links.lww.com/NXG/A207), suggesting that biallelic mutations are not common in LOPD. Of note, we did not examine whether these 2 variants were on the same allele or different allele (compound heterozygous) because they were found only in controls, which

suggests that rare biallelic variants are not involved in LOPD in our cohorts.

To further study a potential role for rare (allele frequency <0.01) or very rare (allele frequency <0.001) *VPS13C* non-synonymous or splice variants in LOPD, a SKAT-O was performed on the variants detailed in table e-2, links.lww.com/NXG/A206. In the French and French Canadian cohort, 33 (6.6%) patients with PD carried a rare variant compared with 49 (6.2%) in controls. In the NY cohort, 43 patients with PD (8.6%) carried a rare variant compared with 29 (11.8%) in controls. In the Israeli cohort, 57 (11.9%) patients with PD carried a rare variant compared with 59 (12.1%) among controls. There was no association between rare variants (French/French Canadian cohort $p = 0.44$, New York cohort $p = 0.34$, and Israel cohort $p = 0.91$) or very rare variants (French/French Canadian cohort $p = 0.17$, New York cohort $p = 0.85$, and Israel cohort $p = 0.89$) and PD. We further examined whether rare variants that are predicted to be deleterious based on CADD score ≥ 12.37 are enriched in PD (the variants included in this analysis are detailed in table e-4, links.lww.com/NXG/A208), and no association was

found (French/French Canadian cohort $p = 0.58$, New York cohort $p = 0.39$, and Israel cohort $p = 0.40$).

A *VPS13C* haplotype including the p.R153H-p.I398I-p.I1132V-p.Q2376Q coding variants is nominally associated with reduced risk for PD

We have identified 14 common coding variants in our cohort of French and French Canadians and 13 such variants in each of the NY and Israeli cohorts. More details on the number of carriers and frequencies can be found in table e-5, links.lww.com/NXG/A209. To test whether common coding variants in *VPS13C* are associated with LOPD, logistic regression models adjusted for age and sex were performed and additional adjustment for ethnicity was included in the New York cohort (see methods). A nominal association was observed in 4 variants (p.R153H [rs12595158, chr15.hg19:g.62316035C>T], p.I398I [rs9635356, chr15.hg19:g.62299603T>G], p.I1132V [rs3784635, chr15.hg19:g.62254989T>C], and p.Q2376Q [rs17238189, chr15.hg19:g.62212781T>C]) with reduced risk for PD in the New York cohort (table 2). These remained nominally significant with and without including adjustment for ethnicity, suggesting that ethnicity has no role in this

Table 2 Four variants forming the protective haplotype found in *VPS13C* and the results of the logistic regression in 3 cohorts

Variant	rs number	nt-substitution	Cohort	N (cases)	N (controls)	Affected MAF	Unaffected MAF	GnomAD MAF ^a	OR (95% CI)	p Value
p.R153H	rs12595158	c.G458A	F/FC	15	27	0.0143	0.0157	0.0734	0.56 (0.26–1.20)	0.1358
			NY	14	16	0.0135	0.0324		0.38 (0.17–0.84)	0.0172
			Israel	16	22	0.0166	0.0225	0.0236	0.70 (0.19–2.6)	0.5940
p.I398I	rs9635356	c.A1194C	F/FC	15	28	0.0143	0.0163	0.0737	0.56 (0.26–1.20)	0.1330
			NY	16	16	0.0154	0.0324		0.42 (0.20–0.91)	0.0274
			Israel	15	19	0.0156	0.0195	0.0214	0.75 (0.19–2.89)	0.6752
p.I1132V	rs3784635	c.A3394G	F/FC	15	26	0.0143	0.0152	0.0726	0.69 (0.32–1.48)	0.3404
			NY	11	18	0.0106	0.0363		0.28 (0.12–0.64)	0.0025
			Israel	14	19	0.0145	0.0195	0.0233	0.65 (0.16–2.65)	0.5444
p.Q2376Q	rs17238189	c.A7128G	F/FC	10	24	0.0095	0.0140	0.0698	0.51 (0.21–1.23)	0.1344
			NY	16	17	0.0154	0.0344		0.42 (0.20–0.90)	0.0245
			Israel	16	20	0.0166	0.0215	0.0212	0.47 (0.07–3.10)	0.4350

Abbreviations: CI = confidence interval; F/FC = French/French Canadian; GnomAD = genome aggregation database; MAF = minor allele frequency; nt = nucleotide; OR = odds ratio.

^a GnomAD_ASJ frequencies were used for the Israeli cohort; all samples are Ashkenazi Jewish.

association and only one of them, p. I1132V (odds ratio 0.28, 95% confidence interval 0.12–0.64, $p = 0.0025$), remained statistically significant after correction for multiple comparisons. In the 2 other cohorts, these variants showed the same directionality as in the New York cohort but did not reach statistical significance (table 2). These 4 variants, p.R153H, p.I398I, p.I1132V, and p.Q2376Q, are in strong or even complete LD (table e-6, links.lww.com/NXG/A210). The most significant tagging SNP of this haplotype, p. I1132V, was validated using Sanger sequencing in all 3 cohorts. Meta-analysis of all the common coding variants showed an association of these 4 linked SNPs with reduced risk for PD (figure), with similar directionality across all cohorts. To examine whether this haplotype may affect AAO of PD, ANOVA with the status of the p. I1132V variant was performed. This variant was not associated with AAO in all 3 cohorts (French/French Canadian cohort $p = 0.65$, New York cohort $p = 0.34$, and Israel cohort $p = 0.99$).

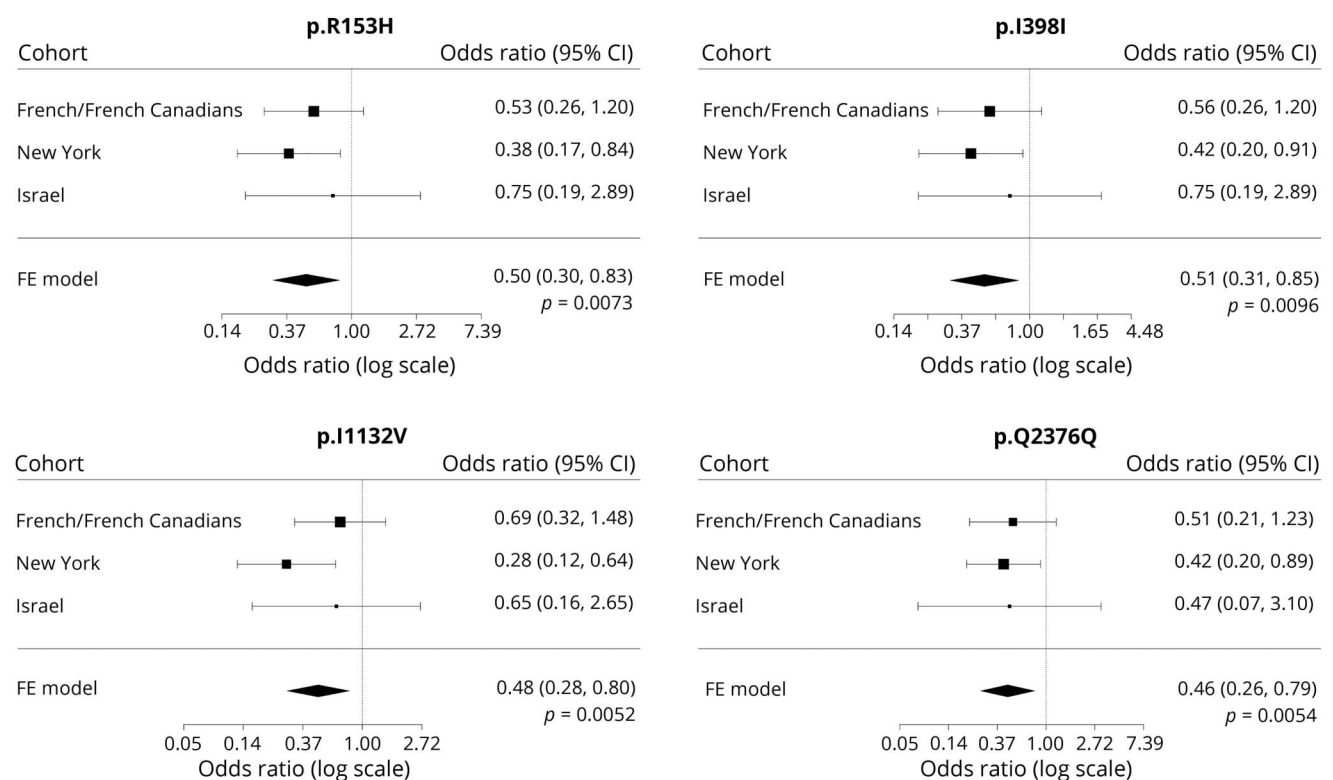
None of these variants were in LD with the known GWAS top hit, rs2414739, and therefore, these associations do not explain the GWAS hit in the *VPS13C* locus. Of all the other common coding variants, only one variant, p.E2008D (rs78071599, chr15.hg19: g.62223303C>G), was in some LD with the GWAS top hit ($D' = 0.808$, $r^2 = 0.006$, table e-7, links.lww.com/NXG/A211), but this variant was not associated with LOPD, and therefore, it also cannot explain the GWAS

hit in our populations. Of interest, an intronic variant, rs78530361 (chr15.hg19: g.62214265C>T), was in LD with the top GWAS SNP ($D' = 1$, $r^2 = 0.003$). Of note, r^2 is low since this intronic SNP has a much lower allele frequency than the top GWAS hit, but every time the rs78530361 SNP is found, it is on an allele which harbors the top GWAS hit rs2414739. However, in our cohorts, this variant was not associated with PD ($p = 0.66$), likely because of its very low r^2 with the GWAS hit.

Discussion

Our study, which included full sequencing of *VPS13C* in 3 cohorts, identified 60 rare *VPS13C* variants (MAF <0.01) that are nonsynonymous or affect splicing and 18 common variants (MAF >0.01) in coding regions of the gene and splice sites. Our results suggest that rare homozygous and compound heterozygous variants are rare in LOPD and probably have importance mainly in EOPD, as previously described. We have identified a potentially protective haplotype, which includes 4 variants, 2 of which are substitutions of amino acids, p.R153H and p.I1132V. The association was mainly driven by the NY cohort, but the 2 other cohorts demonstrated similar directionality of effect and effect size and also contributed to the association. It is unlikely that differences in ethnicity in the NY cohort drove the association because

Figure Forest plots—meta-analyses of 4 *VPS13C* coding variants associated with reduced risk for PD



The forest plots depict the effects of the 4 *VPS13C* coding variants that create the haplotype associated with reduced PD risk in the 3 cohorts studied and their meta-analyzed effect on risk for PD. The results in the random effect model are nearly identical. CI = confidence interval; FE = fixed effect; PD = Parkinson disease.

analysis was with adjustment for ethnicity and analysis without adjustment yielded nearly identical results, ruling out the effect of ethnicity. The other 2 cohorts were of homogeneous ethnicities; therefore, in these cohorts too, ethnicity could not have affected the results. Of interest, this haplotype is not in LD with the top GWAS SNP, rs2414739, suggesting that this may be a secondary association in the *VPS13C* locus, which was not identified in the previous studies. However, this should be considered as preliminary results and needs to be examined in additional cohorts to conclude whether this haplotype is indeed associated with reduced risk for PD. Because the disease-causing mutations reported in *VPS13C* are loss-of-function mutations, a protective effect could occur, for example, because of the gain of function or overexpression. In GTEx (gtexportal.org/home/), these variants were not associated with increased expression or affect splicing. The 2 nonsynonymous variants of this haplotype, p.R153H and p.I1132V, have high CADD scores (22.8 and 13.7, respectively), suggesting that they may affect the protein structure or function. Whether there is such effect and whether it is associated with gain-of-function mutation will need to be examined in follow-up studies. Furthermore, the full sequencing analysis did not identify any coding variant that is in LD, with the original GWAS hit that can explain the GWAS association in this locus. This may suggest that the variant that has the main effect on the risk for PD in the *VPS13C* is outside of the coding and untranslated regions of the gene, likely being a regulatory element.

Previous studies on the top GWAS hit in the *VPS13C* locus demonstrated conflicting results. Although significant associations of the top GWAS hit in this locus (rs2414739) with PD were found in Iranian⁵ and East Asian³ populations, negative results were reported in Taiwanese⁴ and Han Chinese^{6,7} populations. Therefore, it is possible that the association of *VPS13C* with PD is population dependent. Of note, the association in the current study was mainly driven by populations enriched in Ashkenazi Jews, whereas in the French/French Canadian cohort, the differences between patients and controls were much smaller and not statistically significant (table 2). This may suggest that this haplotype association is population specific, and additional studies in different populations are required to answer this question.

In our 3 cohorts, we did not find any very rare homozygous variants with MAF <0.001 and found only 2 carriers of 2 heterozygous variants, both of which were controls (table e-3, links.lww.com/NXG/A207). We were unable to determine if the variants were in cis or trans, but because no carriers of 2 variants were found among patients, it is clear that *VPS13C* biallelic mutations do not contribute to PD in our cohorts. Previously reported cases of PD in carriers of compound heterozygous or homozygous mutations, all shared a specific clinical presentation of PD: early onset, rapid progression, and early cognitive dysfunction.^{8,9} In 1 study, the patient's AAO was 39 and disease progression was moderately severe with psychiatric symptoms and impaired cognition.⁹ In another

study, the 3 patients showed severe phenotypes: AAO of 25, 33, and 46 years, severe and early cognitive dysfunction, and became bedridden at 31, 43, and 58 years, respectively. Considering the young age of one of the compound heterozygous *VPS13C* variant carriers in our cohort (30 years), it is still possible although unlikely that this individual will develop PD in the future. The negative results of the SKAT-O analyses demonstrate that rare heterozygous variants in *VPS13C* do not have an important role in PD in our cohorts.

Our study has several limitations. The differences between patients with PD and controls in sex and mainly age are significant in some of our cohorts. To address this limitation, we included age and sex as covariates in the regression models. Therefore, if the association of the protective haplotype was related to age and not to disease status, we would likely not observe an association in the adjusted model. Furthermore, the association with the haplotype had the same directionality and similar effect size in the NY cohort in which the controls were older (and the association was statistically significant), and in the other 2 cohorts, where the controls were younger, likely ruling out the effect of age. There was no significant difference in the percentage of Ashkenazi Jews between patients and controls in the New York cohort, yet we still performed the regression model with and without ethnicity as a covariate, and in both analyses, the results remained significant. Nevertheless, the fact that our populations are enriched with relatively homogeneous populations such as Ashkenazi Jews and French Canadians requires additional studies in other populations. Another potential limitation is that we could not analyze the effect of CNVs in *VPS13C* with our data. Loss of function and exonic deletions/duplications are rare in gnomAD, found in only 3 individuals at a heterozygous state, and therefore not likely to have a major contribution in PD. However, future studies to examine the potential role of *VPS13C* in PD are required. Furthermore, because no functional experiments were performed in the current study, the potential effects of variants that we report here should be examined in additional studies.

In conclusion, our results suggest that *VPS13C* variants have a limited role in late-onset PD. The potentially PD protective haplotype located within *VPS13C*, which requires additional replications, may suggest that *VPS13C* could be a future target for PD therapeutic development. If naturally occurring genetic variants may reduce PD risk, it is conceivable that drugs that can mimic their effects could be developed. Additional genetic and functional studies will be required to determine if *VPS13C* may be a viable target for PD drug development.

Acknowledgment

The authors thank the patients and control subjects for their participation in this study. This work was financially supported by the Michael J. Fox Foundation, the Canadian Consortium on Neurodegeneration in Aging (CCNA), and the Canadian Glycomics Network (GlycoNet). This research was also undertaken in part to funding from the Canada First

Research Excellence Fund (CFREF) awarded to McGill University for the Healthy Brains for Healthy Lives (HBHL) program. The Columbia University cohort is supported by the Parkinson's Foundation, the National Institutes of Health [K02NS080915 and UL1 TR000040], and the Brookdale Foundation. GAR holds a Canada Research Chair in Genetics of the Nervous System and the Wilder Penfield Chair in Neurosciences. EAF is supported by a foundation grant from the Canadian Institutes of Health Research (FDN grant – 154301). ZGO is supported by the Fonds de recherche du Québec – Santé (FRQS) Chercheurs-boursiers award and by the Young Investigator Award by Parkinson Canada. The access to part of the participants for this research has been made possible thanks to the Quebec Parkinson's Network (rpq-qpn.ca/en/). The authors thank Armaghan Alam, Daniel Rochefort, Helene Catoire, Clotilde Degroot, and Vessela Zaharieva for their assistance.

Study funding

This work was financially supported by the Michael J. Fox Foundation, the Canadian Consortium on Neurodegeneration in Aging (CCNA), and the Canadian Glycomics Network (GlycoNet). This research was also undertaken in part to funding from the Canada First Research Excellence Fund (CFREF), awarded to McGill University for the Healthy Brains for Healthy Lives (HBHL) program. The Columbia University cohort is supported by the Parkinson's Foundation, the NIH [K02NS080915 and UL1 TR000040], and the Brookdale Foundation.

Disclosure

Disclosures available: Neurology.org/NG.

Publication history

Received by *Neurology: Genetics* July 20, 2019. Accepted in final form October 23, 2019.

Appendix Authors

Name	Location	Role	Contribution
Uladzislau Rudakou, BSc	McGill University, Montreal, QC, Canada	Author	Analyzed and interpreted the data; performed validations; drafted the manuscript for intellectual content
Jennifer A. Ruskey, MSc	McGill University, Montreal, QC, Canada	Author	Major role in the acquisition of data; revised the manuscript for intellectual content
Lynne Krohn, MSc	McGill University, Montreal, QC, Canada	Author	Interpreted the data; revised the manuscript for intellectual content
Sandra B. Laurent, BSc	McGill University, Montreal, QC, Canada	Author	Major role in the acquisition of data; Interpreted the data; revised the manuscript for intellectual content

Appendix (continued)

Name	Location	Role	Contribution
Dan Spiegelman, MSc	McGill University, Montreal, QC, Canada	Author	Major role in the acquisition of data; revised the manuscript for intellectual content
Lior Greenbaum, MD, PhD	Sheba Medical Center, Tel Hashomer, Ramat Gan, Israel	Author	Major role in the acquisition of data; revised the manuscript for intellectual content
Gilad Yahalom, MD	Sheba Medical Center, Tel Hashomer, Ramat Gan, Israel	Author	Major role in the acquisition of data; revised the manuscript for intellectual content
Alex Desautels, MD, PhD	Université de Montréal, Montreal, QC, Canada	Author	Major role in the acquisition of data; revised the manuscript for intellectual content
Jacques Y. Montplaisir, MD, PhD	Université de Montréal, Montreal, QC, Canada	Author	Major role in the acquisition of data; revised the manuscript for intellectual content
Stanley Fahn, MD	Columbia University, New York, NY, USA	Author	Major role in the acquisition of data; revised the manuscript for intellectual content
Cheryl H. Waters, MD	Columbia University, New York, NY, USA	Author	Major role in the acquisition of data; revised the manuscript for intellectual content
Oren Levy, MD, PhD	Columbia University, New York, NY, USA	Author	Major role in the acquisition of data; revised the manuscript for intellectual content
Caitlin M. Kehoe, MA	Columbia University, New York, NY, USA	Author	Major role in the acquisition of data; revised the manuscript for intellectual content
Sushma Narayan, MS	Columbia University, New York, NY, USA	Author	Major role in the acquisition of data; revised the manuscript for intellectual content
Yves Dauvilliers, MD, PhD	University of Montpellier, Montpellier, France	Author	Major role in the acquisition of data; revised the manuscript for intellectual content
Nicolas Dupré, MD, FRCP	Université Laval, Québec City, QC, Canada	Author	Major role in the acquisition of data; revised the manuscript for intellectual content
Sharon Hassin-Baer, MD	Sheba Medical Center, Tel Hashomer, Ramat Gan, Israel	Author	Major role in the acquisition of data; revised the manuscript for intellectual content
Roy N. Alcalay, MD, MS	Columbia University, New York, NY, USA	Author	Major role in the acquisition of data; revised the manuscript for intellectual content
Guy A. Rouleau, MD, PhD, FRCP, FRSC	McGill University, Montreal, QC, Canada	Author	Major role in the acquisition of data; revised the manuscript for intellectual content

Continued

Appendix (continued)

Name	Location	Role	Contribution
Edward A. Fon, MD	McGill University, Montreal, QC, Canada	Author	Major role in the acquisition of data; revised the manuscript for intellectual content
Ziv Gan-Or, MD, PhD	McGill University, Montreal, QC, Canada	Author	Designed and conceptualized study; major role in the acquisition of data; assisted with interpretation of the data revised the manuscript for intellectual content; led and coordinated communication among sites.

References

1. Nalls MA, Pankratz N, Lill CM, et al. Large-scale meta-analysis of genome-wide association data identifies six new risk loci for Parkinson's disease. *Nat Genet* 2014;46:989–993.
2. Chang D, Nalls MA, Hallgrímsson IB, et al. A meta-analysis of genome-wide association studies identifies 17 new Parkinson's disease risk loci. *Nat Genet* 2017;49:1511–1516.
3. Zou M, Li R, Wang JY, et al. Association analyses of variants of SIPA1L2, MIR4697, GCH1, VPS13C, and DDRGK1 with Parkinson's disease in East Asians. *Neurobiol Aging* 2018;68:159.e7–159.e14.
4. Chen CM, Chen YC, Chiang MC, et al. Association of GCH1 and MIR4697, but not SIPA1L2 and VPS13C polymorphisms, with Parkinson's disease in Taiwan. *Neurobiol Aging* 2016;39:221–225.
5. Safaralizadeh T, Jamshidi J, Esmaili Shandiz E, et al. SIPA1L2, MIR4697, GCH1 and VPS13C loci and risk of Parkinson's diseases in Iranian population: a case-control study. *J Neurol Sci* 2016;369:1–4.
6. Wang L, Cheng L, Li NN, Yu WJ, Sun XY, Peng R. Association of four new candidate genetic variants with Parkinson's disease in a Han Chinese population. *Am J Med Genet B Neuropsychiatr Genet* 2016;171B:342–347.
7. Yang X, Zheng J, An R, et al. Polymorphism in MIR4697 but not VPS13C, GCH1, or SIPA1L2 is associated with risk of Parkinson's disease in a Han Chinese population. *Neurosci Lett* 2017;650:8–11.
8. Lesage S, Drouot V, Majounie E, et al. Loss of VPS13C function in autosomal-recessive parkinsonism causes mitochondrial dysfunction and increases PINK1/parkin-dependent mitophagy. *Am J Hum Genet* 2016;98:500–513.
9. Schormair B, Kemlink D, Mollenhauer B, et al. Diagnostic exome sequencing in early-onset Parkinson's disease confirms VPS13C as a rare cause of autosomal-recessive Parkinson's disease. *Clin Genet* 2018;93:603–612.
10. Darvish H, Bravo P, Tafakhori A, et al. Identification of a large homozygous VPS13C deletion in a patient with early-onset Parkinsonism. *Mov Disord* 2018;33:1968–1970.
11. Alcalay RN, Levy OA, Wolf P, et al. SCARB2 variants and glucocerebrosidase activity in Parkinson's disease. *NPJ Parkinsons Dis Epub* 2016 Mar 10.
12. Hughes AJ, Daniel SE, Kilford L, Lees AJ. Accuracy of clinical diagnosis of idiopathic Parkinson's disease: a clinico-pathological study of 100 cases. *J Neurol Neurosurg Psychiatry* 1992;55:181–184.
13. O'Roak BJ, Vives L, Fu W, et al. Multiplex targeted sequencing identifies recurrently mutated genes in autism spectrum disorders. *Science* 2012;338:1619–1622.
14. Ross JP, Dupre N, Dauvilliers Y, et al. Analysis of DNAJC13 mutations in French-Canadian/French cohort of Parkinson's disease. *Neurobiol Aging* 2016;45:212 e213–212 e217.
15. Li H, Durbin R. Fast and accurate short read alignment with Burrows-Wheeler transform. *Bioinformatics* 2009;25:1754–1760.
16. McKenna A, Hanna M, Banks E, et al. The Genome Analysis Toolkit: a MapReduce framework for analyzing next-generation DNA sequencing data. *Genome Res* 2010;20:1297–1303.
17. Wang K, Li M, Hakonarson H. ANNOVAR: functional annotation of genetic variants from high-throughput sequencing data. *Nucleic Acids Res* 2010;38:e164.
18. Lek M, Karczewski KJ, Minikel EV, et al. Analysis of protein-coding genetic variation in 60,706 humans. *Nature* 2016;536:285–291.
19. Purcell S, Neale B, Todd-Brown K, et al. PLINK: a tool set for whole-genome association and population-based linkage analyses. *Am J Hum Genet* 2007;81:559–575.
20. Lee S, Emond MJ, Bamshad MJ, et al. Optimal unified approach for rare-variant association testing with application to small-sample case-control whole-exome sequencing studies. *Am J Hum Genet* 2012;91:224–237.
21. Viechtbauer W. Conducting meta-analyses in R with the metafor package. *J Stat Softw* 2010;36.
22. Machiela MJ, Chanock SJ. LDlink: a web-based application for exploring population-specific haplotype structure and linking correlated alleles of possible functional variants. *Bioinformatics* 2015;31:3555–3557.

Neurology[®] Genetics

Analysis of common and rare *VPS13C* variants in late-onset Parkinson disease

Uladzislau Rudakou, Jennifer A. Ruskey, Lynne Krohn, et al.

Neurol Genet 2020;6;

DOI 10.1212/NXG.0000000000000385

This information is current as of January 9, 2020

Updated Information & Services	including high resolution figures, can be found at: http://ng.neurology.org/content/6/1/385.full.html
References	This article cites 20 articles, 3 of which you can access for free at: http://ng.neurology.org/content/6/1/385.full.html##ref-list-1
Subspecialty Collections	This article, along with others on similar topics, appears in the following collection(s): Association studies in genetics http://ng.neurology.org/cgi/collection/association_studies_in_genetics Case control studies http://ng.neurology.org/cgi/collection/case_control_studies Parkinson's disease/Parkinsonism http://ng.neurology.org/cgi/collection/parkinsons_disease_parkinsonism
Permissions & Licensing	Information about reproducing this article in parts (figures, tables) or in its entirety can be found online at: http://ng.neurology.org/misc/about.xhtml#permissions
Reprints	Information about ordering reprints can be found online: http://ng.neurology.org/misc/addir.xhtml#reprintsus

Neurol Genet is an official journal of the American Academy of Neurology. Published since April 2015, it is an open-access, online-only, continuous publication journal. Copyright © 2020 The Author(s). Published by Wolters Kluwer Health, Inc. on behalf of the American Academy of Neurology. All rights reserved. Online ISSN: 2376-7839.

