

Age at symptom onset and death and disease duration in genetic frontotemporal dementia: an international retrospective cohort study



Katrina M Moore, Jennifer Nicholas, Murray Grossman, Corey T McMillan, David J Irwin, Lauren Massimo, Vivianna M Van Deerlin, Jason D Warren, Nick C Fox, Martin N Rossor, Simon Mead, Martina Bocchetta, Bradley F Boeve, David S Knopman, Neill R Graff-Radford, Leah K Forsberg, Rosa Rademakers, Zbigniew K Wszolek, John C van Swieten, Lize C Jiskoot, Lieke H Meeter, Elise GP Dopper, Janne M Papma, Julie S Snowden, Jennifer Saxon, Matthew Jones, Stuart Pickering-Brown, Isabelle Le Ber, Agnès Camuzat, Alexis Brice, Paola Caroppo, Roberta Ghidoni, Michela Pievani, Luisa Benussi, Giuliano Binetti, Bradford C Dickerson, Diane Lucente, Samantha Krivensky, Caroline Graff, Linn Öjierstedt, Marie Fallström, Håkan Thonberg, Nupur Ghoshal, John C Morris, Barbara Borroni, Alberto Benussi, Alessandro Padovani, Daniela Galimberti, Elio Scarpini, Giorgio G Fumagalli, Ian R Mackenzie, Ging-Yuek R Hsiung, Pheth Sengdy, Adam L Boxer, Howie Rosen, Joanne B Taylor, Matthias Synofzik, Carlo Wilke, Patricia Sulzer, John R Hodges, Glenda Halliday, John Kwok, Raquel Sanchez-Valle, Albert Lladó, Sergi Borrego-Ecija, Isabel Santana, Maria Rosário Almeida, Miguel Tábuas-Pereira, Fermin Moreno, Myriam Barandiaran, Begoña Indakoetxea, Johannes Levin, Adrian Danek, James B Rowe, Thomas E Cope, Markus Otto, Sarah Anderl-Straub, Alexandre de Mendonça, Carolina Maruta, Mario Masellis, Sandra E Black, Philippe Couratier, Geraldine Lautrette, Edward D Huey, Sandro Sorbi, Benedetta Nacmias, Robert Laforce Jr, Marie-Pier L Tremblay, Rik Vandenberghe, Philip Van Damme, Emily J Rogalski, Sandra Weintraub, Alexander Gerhard, Chiadi U Onyike, Simon Ducharme, Sokratis G Papageorgiou, Adeline Su Lyn Ng, Amy Brodtmann, Elizabeth Finger, Rita Guerreiro, Jose Bras, Jonathan D Rohrer, for the FTD Prevention Initiative*

Summary

Background Frontotemporal dementia is a heterogenous neurodegenerative disorder, with about a third of cases being genetic. Most of this genetic component is accounted for by mutations in *GRN*, *MAPT*, and *C9orf72*. In this study, we aimed to complement previous phenotypic studies by doing an international study of age at symptom onset, age at death, and disease duration in individuals with mutations in *GRN*, *MAPT*, and *C9orf72*.

Methods In this international, retrospective cohort study, we collected data on age at symptom onset, age at death, and disease duration for patients with pathogenic mutations in the *GRN* and *MAPT* genes and pathological expansions in the *C9orf72* gene through the Frontotemporal Dementia Prevention Initiative and from published papers. We used mixed effects models to explore differences in age at onset, age at death, and disease duration between genetic groups and individual mutations. We also assessed correlations between the age at onset and at death of each individual and the age at onset and at death of their parents and the mean age at onset and at death of their family members. Lastly, we used mixed effects models to investigate the extent to which variability in age at onset and at death could be accounted for by family membership and the specific mutation carried.

Findings Data were available from 3403 individuals from 1492 families: 1433 with *C9orf72* expansions (755 families), 1179 with *GRN* mutations (483 families, 130 different mutations), and 791 with *MAPT* mutations (254 families, 67 different mutations). Mean age at symptom onset and at death was 49·5 years (SD 10·0; onset) and 58·5 years (11·3; death) in the *MAPT* group, 58·2 years (9·8; onset) and 65·3 years (10·9; death) in the *C9orf72* group, and 61·3 years (8·8; onset) and 68·8 years (9·7; death) in the *GRN* group. Mean disease duration was 6·4 years (SD 4·9) in the *C9orf72* group, 7·1 years (3·9) in the *GRN* group, and 9·3 years (6·4) in the *MAPT* group. Individual age at onset and at death was significantly correlated with both parental age at onset and at death and with mean family age at onset and at death in all three groups, with a stronger correlation observed in the *MAPT* group ($r=0\cdot45$ between individual and parental age at onset, $r=0\cdot63$ between individual and mean family age at onset, $r=0\cdot58$ between individual and parental age at death, and $r=0\cdot69$ between individual and mean family age at death) than in either the *C9orf72* group ($r=0\cdot32$ individual and parental age at onset, $r=0\cdot36$ individual and mean family age at onset, $r=0\cdot38$ individual and parental age at death, and $r=0\cdot40$ individual and mean family age at death) or the *GRN* group ($r=0\cdot22$ individual and parental age at onset, $r=0\cdot18$ individual and mean family age at onset, $r=0\cdot22$ individual and parental age at death, and $r=0\cdot32$ individual and mean family age at death). Modelling showed that the variability in age at onset and at death in the *MAPT* group was explained partly by the specific mutation (48%, 95% CI 35–62, for age at onset; 61%, 47–73, for age at death), and even more by family membership (66%, 56–75, for age at onset; 74%, 65–82, for age at death). In the *GRN* group, only 2% (0–10) of the variability of age at onset and 9% (3–21) of that of age of death was explained by the specific mutation, whereas 14% (9–22) of the variability of age at onset and 20% (12–30) of that of age at death was explained by family membership. In the *C9orf72* group, family membership explained 17% (11–26) of the variability of age at onset and 19% (12–29) of that of age at death.

Lancet Neurol 2020; 19: 145–56

Published Online

December 3, 2019

[https://doi.org/10.1016/S1474-4422\(19\)30394-1](https://doi.org/10.1016/S1474-4422(19)30394-1)

This online publication has been corrected. The corrected version first appeared at thelancet.com/neurology on January 21, 2020

See [Comment](#) page 106

*Collaborators listed at the end of the Article

Dementia Research Centre, Department of Neurodegenerative Disease, Institute of Neurology (K M Moore BSc, Prof J D Warren PhD, Prof N C Fox MD, Prof M N Rossor MD, M Bocchetta PhD, J D Rohrer PhD) and Institute of Prion Diseases (Prof S Mead PhD), University College London, London, UK; Department of Medical Statistics, London School of Hygiene & Tropical Medicine, London, UK (J Nicholas PhD); Department of Neurology, Penn Frontotemporal Degeneration Center, University of Pennsylvania, Philadelphia, PA, USA (Prof M Grossman PhD, C T McMillan PhD, D J Irwin PhD, L Massimo PhD, Prof V M Van Deerlin PhD); Department of Neurology, Mayo Clinic, Rochester, MN, USA (Prof B F Boeve MD,

Prof D S Knopman MD, L K Forsberg PhD); Department of Neurology (Prof N R Graff-Radford PhD, Prof Z K Wszolek MD) and Department of Neuroscience (Prof R Rademakers PhD), Mayo Clinic, Jacksonville, FL, USA; Department of Neurology, Erasmus Medical Centre, Rotterdam, Netherlands (Prof J C van Swieten PhD, L C Jiskoot PhD, L H Meeter PhD, E G P Dopper PhD, J M Papma PhD); Cerebral Function Unit, Salford Royal NHS Foundation Trust and Division of Neuroscience and Experimental Psychology, University of Manchester, Manchester, UK (Prof J S Snowden PhD, J Saxon PhD, M Jones PhD, Prof S Pickering-Brown PhD); Institut du Cerveau et de la Moelle épinière & Centre de Référence des Démences Rares ou précoces, Institut de la Mémoire et de la Maladie d'Alzheimer, Assistance Publique-Hôpitaux de Paris, Hôpital de la Pitié-Salpêtrière, Paris, France (I le Ber PhD, A Camuzat BSc, Prof A Brice MD, P Caroppo PhD); Molecular Markers Laboratory (Prof R Ghidoni PhD, L Benussi PhD, Prof G Binetti MD) and Alzheimer's Neuroimaging & Epidemiology Laboratory (M Pievani PhD), Istituto di Ricovero e Cura a Carattere Scientifico Centro San Giovanni di Dio Fatebenefratelli, Brescia, Italy; Frontotemporal Disorders Unit, Department of Neurology, Massachusetts General Hospital and Harvard Medical School, Boston, MA, USA (Prof B C Dickerson MD, D Lucente MS, S Krivensky BS); Center for Alzheimer Research, Division of Neurogenetics, Department of Neurobiology, Care Sciences and Society, Bioclinicum, Karolinska Institutet, Solna, Sweden (Prof C Graff PhD, L Öijerstedt MD, M Fallström MD, H Thonberg MD); Unit for Hereditary Dementias, Theme Aging, Karolinska University Hospital, Solna, Sweden (Prof C Graff, L Öijerstedt, M Fallström, H Thonberg); Department of Neurology, Knight Alzheimer's Disease Research Center, Washington University School of Medicine, St Louis, MO, USA (N Ghoshal PhD,

Interpretation Our study showed that age at symptom onset and at death of people with genetic frontotemporal dementia is influenced by genetic group and, particularly for *MAPT* mutations, by the specific mutation carried and by family membership. Although estimation of age at onset will be an important factor in future pre-symptomatic therapeutic trials for all three genetic groups, our study suggests that data from other members of the family will be particularly helpful only for individuals with *MAPT* mutations. Further work in identifying both genetic and environmental factors that modify phenotype in all groups will be important to improve such estimates.

Funding UK Medical Research Council, National Institute for Health Research, and Alzheimer's Society.

Copyright © 2019 Elsevier Ltd. All rights reserved.

Introduction

Frontotemporal dementia is a genetically and pathologically heterogeneous neurodegenerative disease.¹ The most common clinical subtypes of this disease are behavioural variant frontotemporal dementia, presenting with changes in personality and executive dysfunction, and primary progressive aphasia, in which individuals develop impairment of language processing. Three forms of primary progressive aphasia have been

described: semantic, non-fluent or agrammatic, and logopenic; however, up to 20% of people do not fit the criteria for any of these variants and are categorised as having primary progressive aphasia not otherwise specified.² Both behavioural variant frontotemporal dementia and primary progressive aphasia overlap with amyotrophic lateral sclerosis and with the atypical parkinsonian syndromes corticobasal syndrome and progressive supranuclear palsy.¹

Research in context

Evidence before this study

We searched PubMed for articles on genetic frontotemporal dementia with no language restrictions from database inception up to July 1, 2017, using the following terms: "frontotemporal dementia AND genetics", "progranulin OR *GRN*", "tau OR *MAPT*", and "chromosome 9 open reading frame 72 OR *C9orf72*", focusing on studies that reported age at symptom onset, age at death or disease duration of individuals with symptoms. No studies were found that had systematically investigated age at symptom onset, age at death, or disease duration across all the different genetic groups and the different mutations found within the groups. However, evidence from cohort studies and individual case series suggested that the age at symptom onset, age at death, and disease duration were highly variable across the genes implicated in frontotemporal dementia. Age-related penetrance was described in individuals with *GRN* and *C9orf72* mutations, with *MAPT* mutations usually being fully penetrant. We found a generational difference in age at symptom onset, with an earlier onset in later generations occurring in individuals with *GRN* or *C9orf72* mutations. Phenotypic differences in age at symptom onset have not been studied in detail yet, but one study showed a shorter disease duration in individuals with a diagnosis of amyotrophic lateral sclerosis in the *C9orf72* group compared with those with other diagnoses, and another study showed an earlier age at symptom onset in this group compared with that of other diagnoses.

Added value of this study

To our knowledge, this is the largest international study to date investigating individual age at symptom onset, age at death, and disease duration in patients with genetic frontotemporal dementia, across all the three main genetic groups (*C9orf72*,

GRN, and *MAPT*), and all known mutations within the *GRN* and *MAPT* groups. Our study provides important evidence about the factors underlying age at symptom onset, age at death, and disease duration in the different groups. We showed that only in the *MAPT* mutation group were age at symptom onset and at death highly correlated with both parental and mean family ages at symptom onset and at death, with variability in these ages explained partly by the specific mutation and more so by family membership. Such correlations were weaker in the other two groups, with the variability in age at symptom onset and age at death for individuals with *GRN* mutations and *C9orf72* expansions not accounted for particularly by family membership or, for individuals with *GRN* mutations, by the specific mutation. This is the first time that such key differences between genetic frontotemporal dementia groups have been shown.

Implications of all the available evidence

Optimal therapeutic trial design will be important in genetic frontotemporal dementia, and particularly because many trials will aim to include presymptomatic individuals who are expected to be in proximity to symptom onset. Our study suggests that in individuals with *MAPT* mutations data from other family members will be particularly helpful in estimating time from symptom onset. Further work is needed to understand the variability in the other genetic groups, and other proximity markers, either individually or in combination, are likely to be required to refine the estimation of time to symptom onset in individuals with *GRN* or *C9orf72* mutations. In the meantime, the available data will provide clinicians and family members with a better understanding of the individual risk of probable symptom onset and time to death in each genetic group and within individual mutations.

About a third of frontotemporal dementia cases are genetic,³ with mutations in multiple genes shown to be causative of this disease. However, most of the heritability of frontotemporal dementia is accounted for by mutations in three genes: progranulin (*GRN*), microtubule-associated protein tau (*MAPT*), and chromosome 9 open reading frame 72 (*C9orf72*; also known as *C9orf72*-SMCR8 complex subunit). Although much has been learned over the past decade about the clinical features of these genetic forms of frontotemporal dementia, most studies exploring age at symptom onset and disease duration have been small and geographically restricted.^{4–6} In particular, although individual case series have suggested that such phenotypic characteristics can be quite variable, no studies have systematically investigated these factors across all the different genetic groups and the different mutations found within these groups.

Therefore, in this large international study, we aimed to analyse phenotypic characteristics of the main three forms of genetic frontotemporal dementia, including ages at symptom onset and death and disease duration, as well as examining the effect of mutation type and family membership on these factors.

Methods

Study design and participants

In this international retrospective cohort study, we collected data from centres that are part of the Frontotemporal Dementia Prevention Initiative (FPI) and through a literature review of publications. The FPI is a group connecting natural history cohort studies of genetic frontotemporal dementia: the Genetic Frontotemporal Dementia Initiative (GENFI),⁷ Advancing Research and Treatment for Frontotemporal Lobar Degeneration (ARTFL), Longitudinal Evaluation of Familial Frontotemporal Dementia Subjects (LEFFTDS), and the Dominantly Inherited Non-Alzheimer's Dementias (DINAD) studies. These research studies include most of the centres investigating genetic frontotemporal dementia in Europe and eastern Canada (GENFI), USA and western Canada (ARTFL and LEFFTDS), and Australia (DINAD). In total, 33 centres across the world (12 countries; appendix p 20) provided participant data for our study. We included all known pathogenic mutations in the *GRN*, *MAPT*, and *C9orf72* genes in our study. Families with intermediate length expansions of *C9orf72* were not included in the study. All mutations were reviewed by two geneticists (RG and JB) to examine pathogenicity and were only included if both agreed on their probable pathogenic nature (full inclusion and exclusion criteria are in the appendix, p 2). Local ethics committees at each of the sites approved the study and data from participants was provided through informed written consent.

Procedures

Participant data collected from FPI centres included genetic group, individual mutation (for participants with

mutations in *GRN* and *MAPT*), sex, clinical phenotype, age at symptom onset (defined by the onset of progressive behavioural, cognitive, or motor symptoms reported either by an informant [usually a family member] or, for non-behavioural symptoms, by the patient themselves), age at death, and relationship to other affected family members.

For the literature review, we assessed publications cited in the Alzheimer Disease & Frontotemporal Dementia Mutation database, and supplemented this by a detailed search of PubMed (done between Jan 1, 2015, and July 1, 2017) for other publications with data for age at symptom onset, age at death, or disease duration in people with genetic frontotemporal dementia: this identified 308 journal articles. To avoid potential double reporting, centres were asked to provide a list of publications relevant to their dataset. These lists were then manually examined for possible duplicates, which were removed when identified.

Statistical analysis

We grouped participants into a *GRN*, *MAPT*, or *C9orf72* group according to the mutation present. We calculated the numbers and percentages of participants within each genetic group by geographic location and clinical phenotype. We used a χ^2 test to compare sex distribution in each of the genetic groups. We calculated means and SDs for age at symptom onset, age at death, and disease duration in each genetic group and in the most common mutations in the *MAPT* and *GRN* groups (defined as those identified in the greatest number of individuals in the study). We used mixed effects models to examine differences in age at symptom onset, age at death, and disease duration between genetic groups (*GRN*, *MAPT*, and *C9orf72*), between the most common mutations in the *GRN* and *MAPT* groups, between an earlier (first) and later (second) generation of family members in all genetic groups, between men and women within each genetic group, and between the main clinical phenotypes within each genetic group. Analyses accounted for relatedness by including family membership as a random effect. We calculated Pearson correlation coefficients to explore the relationship between an individual's age at symptom onset (or death) and the age at symptom onset (or death) of their affected parent and the association between an individual's age at symptom onset (or death) and the average age at symptom onset (or death) of other members of the same family. Lastly, we also used mixed effects models to explore the extent to which variability in age at symptom onset and at death were explained by family membership (exploring variability both within and between families) and the specific mutation carried (in *GRN* and *MAPT* groups). Detailed statistical methods are shown in the appendix (pp 15–19). All statistical analyses were done with Stata (v.14 or later).

Prof J C Morris MD); Centre for Neurodegenerative Disorders, Department of Clinical and Experimental Sciences, University of Brescia, Brescia, Italy (B Borroni PhD, A Benussi PhD, Prof A Padovani PhD); Department of Biomedical, Surgical and Dental Sciences (D Galimberti PhD) and Department of Pathophysiology and Transplantation (Prof E Scarpini MD, G G Fumagalli MD), Centro Dino Ferrari, University of Milan, Milan, Italy; Istituto di Ricovero e Cura a Carattere Scientifico Fondazione Ca' Granda, Ospedale Maggiore Policlinico, Milan, Italy (D Galimberti, Prof E Scarpini, G G Fumagalli); Department of Neurosciences, Psychology, Drug Research and Child Health, University of Florence, Florence, Italy (G G Fumagalli, Prof S Sorbi PhD, B Nacmias PhD); Division of Neurology, Department of Medicine, University of British Columbia, Vancouver, BC, Canada (Prof I R Mackenzie MD, G-Y R Hsiung MD, P Sengdy PhD); Department of Neurology, Memory and Aging Center, University of California San Francisco, San Francisco, CA, USA (Prof A L Boxer PhD, Prof H Rosen PhD, J B Taylor MS); Department of Neurodegenerative Diseases, Center for Neurology and Hertie-Institute for Clinical Brain Research, Tübingen, Germany (Prof M Synofzik MD, C Wilke MD, P Sulzer MSc); German Center for Neurodegenerative Diseases, Tübingen, Germany (Prof M Synofzik, C Wilke, P Sulzer); Brain and Mind Centre & Central Clinical School, Faculty of Medicine and Health, University of Sydney, Sydney, NSW, Australia (Prof J R Hodges PhD, Prof G Halliday PhD, J Kwok PhD); Alzheimer's Disease and Other Cognitive Disorders Unit, Hospital Clinic, Institut d'Investigacions Biomèdiques August Pi i Sunyer, Barcelona, Spain (R Sanchez-Valle MD, A Lladó MD, S Borrego-Ecija MD); Center for Neuroscience and Cell Biology (I Santana PhD, M R Almeida PhD) and Faculty of Medicine (I Santana), University of Coimbra, Coimbra, Portugal; Neurology

| | GRN (n=1179) | MAPT (n=791) | C9orf72 (n=1433) | Difference MAPT vs GRN | Difference C9orf72 vs GRN | Difference C9orf72 vs MAPT | p value MAPT vs GRN | p value C9orf72 vs GRN | p value C9orf72 vs MAPT |
|------------------------------|----------------------|-----------------------|-----------------------|---------------------------|------------------------------|-------------------------------|------------------------|---------------------------|----------------------------|
| Sex (n [%]) | .. | .. | .. | .. | .. | .. | 0.0015 | <0.0001 | 0.18 |
| Men | 490 (41.6%) | 386 (48.8%) | 742 (51.8%) | .. | .. | .. | .. | .. | .. |
| Women | 689 (58.4%) | 405 (51.2%) | 691 (48.2%) | .. | .. | .. | .. | .. | .. |
| Number of families | 483 | 254 | 755 | .. | .. | .. | .. | .. | .. |
| Age at symptom onset (years) | .. | .. | .. | -11.8 (-13.0 to -10.6) | -2.8 (-3.8 to -1.9) | 9.0 (7.8 to 10.1) | <0.0001 | <0.0001 | <0.0001 |
| Mean (SD; n) | 61.3 (8.8; n=967) | 49.5 (10.0; n=609) | 58.2 (9.8; n=1076) | .. | .. | .. | .. | .. | .. |
| Range | 25-90 | 17-82 | 20-91 | .. | .. | .. | .. | .. | .. |
| Age at death (years) | .. | .. | .. | -10.7 (-12.3 to -9.1) | -3.5 (-4.9 to -2.2) | 7.2 (5.7 to 8.6) | <0.0001 | <0.0001 | <0.0001 |
| Mean (SD; n) | 68.8 (9.7; n=656) | 58.5 (11.3; n=485) | 65.3 (10.9; n=839) | .. | .. | .. | .. | .. | .. |
| Range | 42-98 | 24-93 | 26-97 | .. | .. | .. | .. | .. | .. |
| Disease duration (years) | .. | .. | .. | 0.18 (0.08 to 0.29) | -0.26 (-0.35 to -0.17) | -0.44 (-0.54 to -0.34) | 0.0005 | <0.0001 | <0.0001 |
| Mean (SD; n) | 7.1 (3.9; n=548) | 9.3 (6.4; n=394) | 6.4 (4.9; n=618) | .. | .. | .. | .. | .. | .. |
| Range | 0-27 | 0-45 | 0-36 | .. | .. | .. | .. | .. | .. |

For age at symptom onset, age at death, and disease duration, differences are adjusted mean differences (natural log values for disease duration) with 95% CIs. For sex differences, p values calculated with a χ^2 test. For age at symptom onset, age at death, and disease duration, p values calculated with mixed effects models.

Table 1: Patient demographics and age at symptom onset, age at death, and disease duration in each of the three genetic groups

Department, Centro Hospitalar e Universitário de Coimbra, Coimbra, Portugal (I Santana, M Tábuas-Pereira MD); Cognitive Disorders Unit, Department of Neurology, Donostia University Hospital, San Sebastian, Spain (F Moreno PhD, M Barandiaran PhD, B Indakoetxea MD); Neuroscience Area, Biodonostia Health Research Institute, San Sebastian, Spain (F Moreno, M Barandiaran, B Indakoetxea); Center for Networked Biomedical Research on Neurodegenerative Disease, Carlos III Health Institute, Madrid, Spain (F Moreno, M Barandiaran, B Indakoetxea); Department of Neurology, Ludwig-Maximilians-Universität München, Munich, Germany (J Levin MD, Prof A Danek MD); German Center for Neurodegenerative Diseases, Munich, Germany (J Levin); Munich Cluster for Systems Neurology, Munich, Germany (J Levin); Department of Clinical Neurosciences, University of Cambridge, Cambridge, UK (Prof J B Rowe PhD, T E Cope PhD); Department of Neurology, University of Ulm,

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results

Our combined dataset comprised 3403 symptomatic individuals from 1492 families who had data available for one or more of age at symptom onset, age at death, disease duration, and clinical phenotype (table 1): 1433 individuals with C9orf72 expansions (from 755 families), 1179 with GRN mutations (483 families), and 791 with MAPT mutations (254 families).

In total, 130 GRN mutations and 67 MAPT mutations were identified and all were included in the study (appendix pp 5-10). We found 78 GRN and 45 MAPT pathogenic mutations through the Alzheimer Disease & Frontotemporal Dementia Mutation database, 35 GRN and 18 MAPT variants, which were not included in the database, through a PubMed search, and the FPI centres provided data on an additional 17 GRN and four MAPT variants not previously described in the literature (appendix p 2). The most common GRN mutations were Thr272fs (rs63749877; 201 individuals, 95 families), Arg493X (rs63751294; 55 individuals, 22 families), IVS7-1G→A (50 individuals, 18 families), Cys31fs (rs63751057, 47 individuals, 10 families), Gly35fs (rs63751073, 42 individuals, 10 families), and Ala9Asp (rs63751243, 37 individuals, four families). The most common MAPT mutations

were Pro301Leu (rs63751273, 234 individuals, 59 families), IVS10+16C→T (rs63751011; 149 individuals, 48 families), Arg406Trp (rs63750424, 67 individuals, nine families), and Asn279Lys (rs63750756, 44 individuals, 17 families).

Overall, the most prevalent genetic group was that comprising individuals carrying a C9orf72 expansion (1433 [42.1%] of 3403 individuals), followed by individuals with GRN mutations (1179 [34.6%]), with individuals carrying MAPT mutations comprising the least common group (791 [23.2%]; figure 1). However, we observed geographical variability in the distribution of these mutations, with a different spread of frequencies among the three genetic groups in some countries and regions: individuals with GRN mutations were more common than those of other groups in Italy (289 [66%] of 438 individuals) and, to a lesser extent, in Spain (76 [49%] of 155); whereas individuals with MAPT mutations were found more frequently in the Netherlands (81 [40%] of 204) and the US west coast (71 [47%] of 150; appendix pp 20-23).

Although behavioural variant frontotemporal dementia was the most common diagnosis in each genetic group, we observed phenotypic variability across the different mutations (table 2; appendix pp 24-32). Both C9orf72 and MAPT groups contained approximately equal numbers of men and women (table 1, appendix pp 33-34). However, the GRN group had a significant overrepresentation of women compared with both the C9orf72 group and the MAPT group.

The mean age at symptom onset was lowest for the MAPT group, which was significantly lower than those of the GRN and C9orf72 groups (p<0.0001 for each

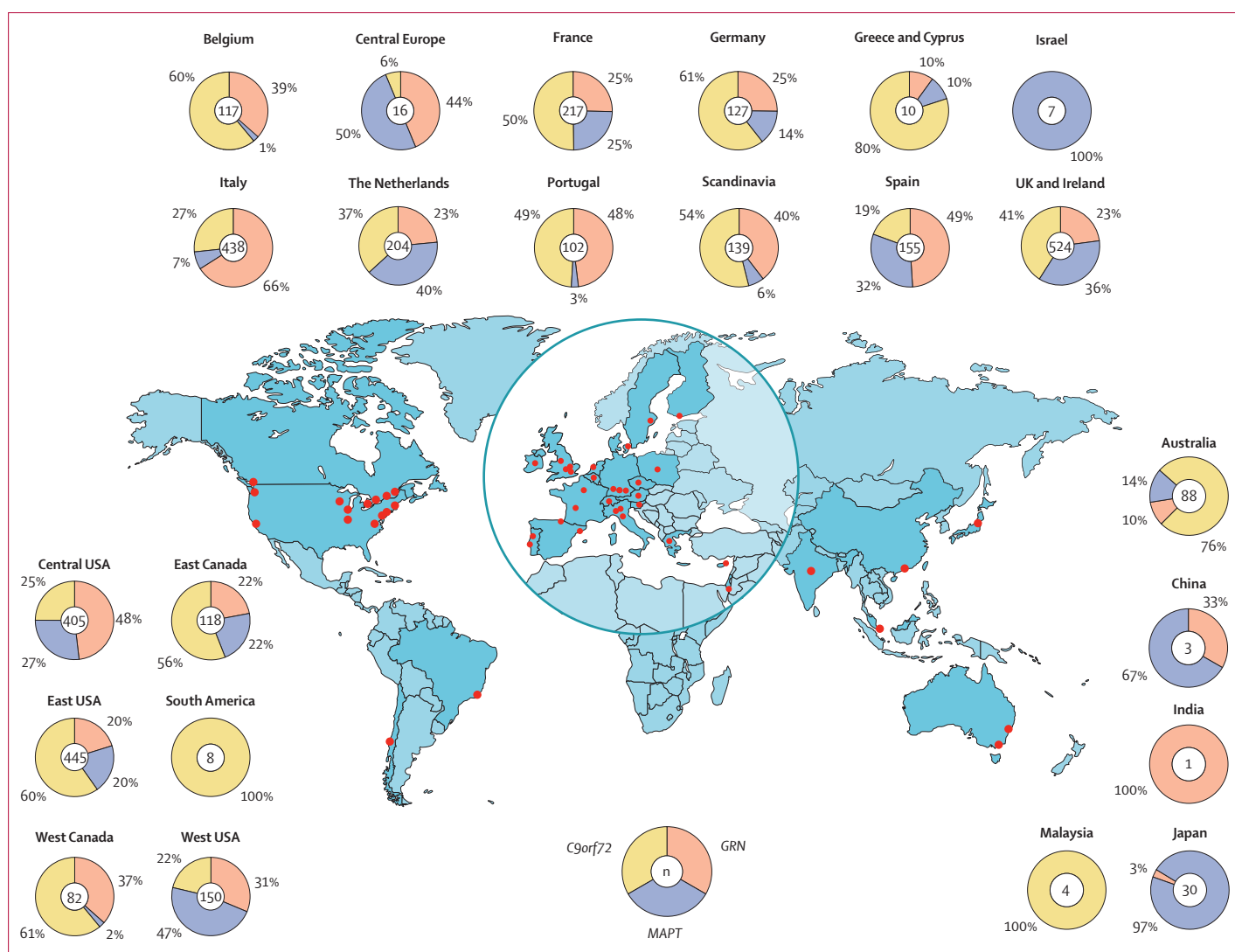


Figure 1: Frequency of each of the three genetic groups by geographic location

Countries with data included in the study are shown in dark blue (appendix p 20). Individual centres are shown as red dots on the map. Pie charts show relative frequency of each of the three genetic groups within a geographical area, with the number in the centre representing the number of cases included within that area.

comparison). The *C9orf72* group had the second lowest age, which was significantly lower than that of the *GRN* group ($p < 0.0001$; table 1, appendix pp 35–36). However, we observed a wide range of age at symptom onset within each of the genetic groups, from the 20s to the 90s in the *GRN* and *C9orf72* groups and from age 17 years to the 80s in the *MAPT* group (figure 2, appendix pp 36). Cumulative probability curves for age at symptom onset in each of the genetic groups are shown in figure 3A (appendix p 39).

We also observed a wide range of age at symptom onset among *GRN* and *MAPT* mutations (appendix pp 6–10). We plotted cumulative probability curves for age at symptom onset for the most common *GRN* (figure 3B) and *MAPT* (figure 3C) mutations (appendix p 39). These curves largely overlapped for the *GRN* mutations, without any significant difference between groups. By contrast, we

observed a significant difference between *MAPT* mutations, with the Asn279Lys mutation group having a lower age at symptom onset (mean 43.8 years, SD 6.7) than that of the other groups ($p \leq 0.0026$ for all comparisons; appendix p 40). The generational analysis showed a significantly lower age at symptom onset in the second (later) generation than the first (earlier generation) in all three groups: mean age was 65.5 years (SD 9.1) in *GRN* first generation and 60.7 years (8.9) in *GRN* second generation ($p < 0.0001$); 62.3 years (10.9) in *C9orf72* first generation and 56.7 years (11.0) in *C9orf72* second generation ($p < 0.0001$); and 51.4 years (9.5) in *MAPT* first generation and 49.6 years (10.0) in *MAPT* second generation ($p = 0.011$; appendix pp 41–43).

We found no significant differences in age at symptom onset between men and women in the *MAPT* group

Ulm, Germany (Prof M Otto MD, S Anderl-Straub PhD); Faculty of Medicine, University of Lisbon, Lisbon, Portugal (Prof A de Mendonça PhD, C Maruta PhD); Division of Neurology, Department of Medicine, Hurvitz Brain Sciences Program, Sunnybrook Health Sciences Centre, University of Toronto, Toronto, ON, Canada (M Masellis PhD, Prof S E Black MD); Centre de Compétence Démences Rares, Centre Hospitalier et Universitaire Limoges, Limoges, France (Prof P Couratier PhD, G Lautrette MD); Departments

| | GRN (n=1179) | MAPT (n=791) | C9orf72 (n=1433) |
|---|-----------------|-----------------|---------------------|
| Diagnoses within the frontotemporal dementia spectrum | | | |
| Behavioural variant frontotemporal dementia | 446 (37.8%) | 354 (44.8%) | 450 (31.4%) |
| Non-fluent variant primary progressive aphasia | 107 (9.1%) | 14 (1.8%) | 26 (1.8%) |
| Semantic variant primary progressive aphasia | 13 (1.1%) | 14 (1.8%) | 13 (0.9%) |
| Logopenic variant primary progressive aphasia | 4 (0.3%) | 0 (0%) | 3 (0.2%) |
| Primary progressive aphasia not otherwise specified* | 36 (3.1%) | 2 (0.3%) | 4 (0.3%) |
| Frontotemporal dementia with amyotrophic lateral sclerosis | 7 (0.6%) | 2 (0.3%) | 157 (11.0%) |
| Amyotrophic lateral sclerosis | 7 (0.6%) | 1 (0.1%) | 276 (19.3%) |
| Corticobasal syndrome | 47 (4.0%) | 14 (1.8%) | 2 (0.1%) |
| Progressive supranuclear palsy† | 0 (0%) | 33 (4.2%) | 1 (0.1%) |
| Diagnoses outside the frontotemporal dementia spectrum | | | |
| Alzheimer's disease | 97 (8.2%) | 24 (3.0%) | 84 (5.9%) |
| Huntington's disease | 0 (0%) | 1 (0.1%) | 4 (0.3%) |
| Parkinson's disease | 16 (1.4%) | 39 (4.9%) | 15 (1.0%) |
| Dementia with Lewy Bodies | 4 (0.3%) | 1 (0.1%) | 5 (0.3%) |
| Vascular dementia | 9 (0.8%) | 1 (0.1%) | 7 (0.5%) |
| Dementia not otherwise specified* | 361 (30.6%) | 274 (34.6%) | 362 (25.3%) |
| Other | 25 (2.1%) | 17 (2.1%) | 24 (1.7%) |

*Does not meet criteria for a specific subtype. †Richardson's syndrome.

Table 2: Clinical diagnoses in each of the three genetic groups

of Psychiatry and Neurology, Columbia University, New York, NY, USA (E D Huey MD); Istituto di Ricovero e Cura a Carattere Scientifico Fondazione Don Carlo Gnocchi, Florence, Italy (Prof S Sorbi); Clinique Interdisciplinaire de Mémoire, Département des Sciences Neurologiques, Hôpital de l'Enfant-Jésus, and Faculté de Médecine, Université Laval, Québec, QC, Canada (R Laforce Jr MD, M-P L Tremblay PhD); Department of Neurology, University Hospitals Leuven, Leuven, Belgium (Prof R Vandenbergh PhD, Prof P V Damme PhD); Center for Brain & Disease Research, VIB, Leuven, Belgium (Prof P V Damme); Mesulam Center for Cognitive Neurology and Alzheimer's Disease, Northwestern University, Chicago, IL, USA (E J Rogalski PhD, S Weintraub PhD); Wolfson Molecular Imaging Centre, University of Manchester, Manchester, UK (A Gerhard MD); Departments of Nuclear Medicine and Geriatric Medicine, University Hospital Essen, Essen, Germany (A Gerhard); Division of Geriatric Psychiatry and Neuropsychiatry, Johns Hopkins University School of

(appendix p 44). However, in the GRN group, women were significantly older at symptom onset (61.8 years, SD 9.2) than men (60.5 years, 8.3; $p=0.019$), with the same observed in the C9orf72 group (58.9 years, SD 9.6, in women, compared with 57.7 years, 10.0, in men [$p=0.041$]).

In the C9orf72 group, we found no significant differences in mean age at symptom onset between individuals with different clinical phenotypes, except for those with a diagnosis of Alzheimer's disease (appendix pp 45–46). These individuals were significantly older at symptom onset than individuals with other phenotypes (mean 65.1 years, SD 10.6; $p<0.0001$ for all comparisons except for that with primary progressive aphasia [$p=0.010$]). Similarly, we found no significant differences in age at symptom onset between individuals with different clinical phenotypes in the GRN group, except for those with a diagnosis of Alzheimer's disease, who were significantly older at symptom onset (mean 66.4 years, SD 8.1) than individuals with other phenotypes ($p<0.0001$ for all comparisons). In the MAPT group, we found no significant differences in age at symptom onset between individuals with behavioural variant frontotemporal dementia and those with primary progressive aphasia; however, individuals with Alzheimer's disease were significantly older at symptom onset (mean 56.7 years, SD 11.1) than those with behavioural variant frontotemporal dementia ($p=0.0006$), primary progressive aphasia ($p=0.013$), and a combined corticobasal syndrome and progressive supranuclear palsy (atypical parkinsonism; $p<0.0001$). Furthermore, individuals in the MAPT group with atypical parkinsonism were significantly younger at symptom onset (mean 44.9 years, SD 7.8) than those with other

phenotypes (individuals with atypical parkinsonism vs those with behavioural variant frontotemporal dementia $p=0.013$; vs individuals with primary progressive aphasia $p=0.037$).

The mean age at death was lowest in individuals with MAPT mutations and highest in those with GRN mutations ($p<0.0001$ for all comparisons between groups; table 1). Age at death was variable within genetic groups (table 1, figure 2) and within individual mutations (appendix pp 6–10, 37). As with age at symptom onset, we found no significant differences in age at death between men and women in the MAPT group, but found significant differences between men and women in the GRN group (mean 69.4 years, SD 10.2, in women vs 67.8 years, 8.8, in men; $p=0.029$) and C9orf72 group (66.1 years, 11.0, in women vs 64.6 years, 10.8, in men; $p=0.034$; appendix p 44).

As with age at symptom onset, individuals with a diagnosis of Alzheimer's disease in all three genetic groups were significantly older at death than individuals with other phenotypes (appendix pp 45–46). In the C9orf72 group, individuals with a diagnosis of amyotrophic lateral sclerosis were significantly younger (mean 59.2 years, SD 9.7) at death compared with those with a diagnosis of frontotemporal dementia with amyotrophic lateral sclerosis (62.1 years, 8.9; $p=0.014$) and those with a diagnosis of behavioural variant frontotemporal dementia (64.6 years, 9.0; $p<0.0001$). In turn, individuals with a diagnosis of frontotemporal dementia with amyotrophic lateral sclerosis were younger at death than those with a diagnosis of behavioural variant frontotemporal dementia ($p=0.014$). In the MAPT group, individuals with a diagnosis of atypical parkinsonism were significantly younger at death (mean 52.8 years, SD 8.9) compared with those with a diagnosis of behavioural variant frontotemporal dementia (60.6 years, 9.9; $p=0.030$) and those with a diagnosis of primary progressive aphasia (60.9 years, 15.2; $p=0.036$).

The mean disease duration was lowest for individuals with C9orf72 expansions, followed by those with GRN mutations, and those with MAPT mutations ($p\leq0.0005$ for each comparison; table 1). However, within each genetic group, several individuals survived for many decades; the longest surviving individuals lived 27 years from symptom onset in the GRN group, 36 years in the C9orf72 group, and 45 years in the MAPT group (table 1, figure 2, appendix p 38). Although variability within individual mutations existed (appendix pp 6–10, 38), mean disease duration was similar across the GRN group, except for a significantly longer disease duration in individuals with an Ala9Asp mutation compared with those with Gly35fs, Thr272fs, and Arg493X mutations (appendix p 40). We found a greater variability in the mean disease duration in the MAPT group than in the GRN group. Individuals with an Arg406Trp mutation had a significantly longer disease duration than those with Pro301Leu and Asn279Lys mutations, and individuals with an IVS10+16C→T

mutation had a significantly longer disease duration than those with Pro301Leu mutations (appendix pp 40, 47–48).

We found no significant differences in disease duration between men and women in any of the groups (appendix p 44). We observed no significant differences in disease duration between clinical phenotypes in the *GRN* and *MAPT* groups (appendix pp 45–46). However, individuals with *C9orf72* expansions and a diagnosis of amyotrophic lateral sclerosis had a significantly lower disease duration (mean 2.9 years, SD 2.8) than those of the other groups ($p < 0.0001$ for all comparisons); individuals with *C9orf72* expansions and a diagnosis of frontotemporal dementia with amyotrophic lateral sclerosis also had a lower disease duration (5.0 years, 4.2) than that of those with *C9orf72* expansions and behavioural variant frontotemporal dementia (7.8 years, 4.4; $p < 0.0001$), primary progressive aphasia (7.5 years, 4.8; $p = 0.0016$), and Alzheimer's disease (10.4 years, 4.9; $p < 0.0001$; appendix pp 45–46).

Individual age at symptom onset significantly correlated with both parental and mean family age at symptom onset in all three genetic groups ($p < 0.0001$; figure 4); in each group, individual age at symptom onset either had a similar correlation with parental and mean family age or a stronger correlation with mean family age than with parental age. The strength of these correlations varied across the genetic groups, being strongest in the *MAPT* group and weakest in the *GRN* group (figure 4). As with age at symptom onset, individual age at death significantly correlated with both parental age at death and mean family age at death in all three genetic groups ($p < 0.0001$). We observed a similar pattern to that of age at symptom onset in the three genetic groups: the *MAPT* group had the strongest correlation ($r = 0.69$ for mean family age at death, $r = 0.58$ for parental age at death), followed by the *C9orf72* group ($r = 0.40$, $r = 0.38$) and the *GRN* group ($r = 0.32$, $r = 0.22$).

We found significant differences between the three mutation groups in the inter-family and intra-family variability of age at symptom onset (both $p < 0.0001$; appendix p 49). Family membership explained 66% (95% CI 56–75) of this variability in individuals with *MAPT* mutations, but only 14% (9–22) in those with *GRN* mutations and 17% (11–26) in those with *C9orf72* expansions. We observed a significant difference between the *GRN* and *MAPT* groups in the between-mutation variability in age at symptom onset ($p < 0.0001$): in the *GRN* group, only 2% (95% CI 0–10) of the variability was explained by the specific mutation, whereas in the *MAPT* group, 48% (35–62) of the variability was explained by the specific mutation.

Significant differences were also found between the three genetic groups in the variability of inter-family and intra-family age at death (both $p < 0.0001$; appendix p 49). Family membership explained 74% (95% CI 65–82) of this variability in individuals with *MAPT* mutations, but only 20% (12–30) in those with *GRN* mutations and

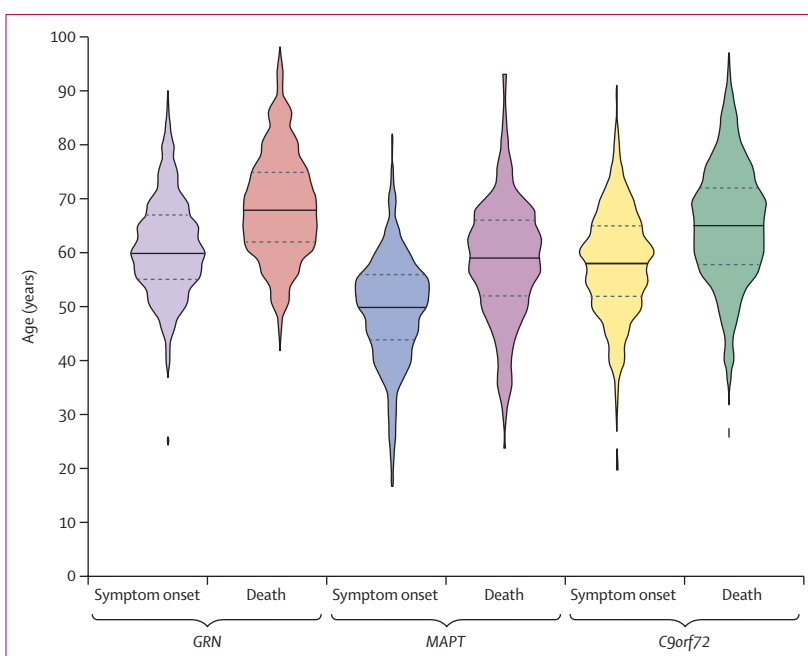


Figure 2: Violin plots of age at symptom onset and at death for the three genetic groups
Data are median (bold lines) with IQR (dashed lines).

19% (12–29) in those with *C9orf72* expansions. We also found a significant difference between the *GRN* and *MAPT* groups in the between-mutation variability in age at death ($p < 0.0001$): in the *GRN* group, only 9% (95% CI 3–21) of the variability was explained by the specific mutation, whereas in the *MAPT* group, 61% (47–73) of the variability was explained by the specific mutation.

Discussion

To our knowledge, we report in this study the largest dataset of age at onset, age at death, and disease duration in individuals with genetic frontotemporal dementia to date, incorporating data from across the world for the three main genetic groups and for all reported mutations in the *GRN* and *MAPT* groups. Our study provides evidence that an individual's age at symptom onset and death in genetic frontotemporal dementia is modulated by both the individual mutation carried and family membership and varies by clinical phenotype and sex, with the strongest effect of these factors seen in individuals with *MAPT* mutations.

Our study provides further evidence that genetic frontotemporal dementia is a disorder that can occur throughout adult life, with symptom onset occurring from as early as the late teens to age 90 years or older. Although we did not account for individuals with mutations who were unaffected in the analysis, our findings are consistent with previous studies showing age-related penetrance in the *GRN*⁸ and *C9orf72*⁹ groups, with individuals developing symptoms at age 90 years and older. A leftwards shift towards younger ages is evident in the penetrance curve in individuals with *MAPT* mutations (figure 3A) but

Medicine, Baltimore, MD, USA (C U Onyike MD); Montreal Neurological Institute, McConnell Brain Imaging Centre, McGill University Health Centre, McGill University, Montreal, QC, Canada (S Ducharme MD); Cognitive Disorders/Dementia Unit, 2nd Department of Neurology, National and Kapodistrian University of Athens, Attikon University General Hospital, Athens, Greece (S G Papageorgiou PhD); Department of Neurology, National Neuroscience Institute, Singapore, Singapore (A S L Ng MD); Florey Institute of Neuroscience and Mental Health, Melbourne, VIC, Australia (A Brodtmann PhD); Department of Clinical Neurological Sciences, University of Western Ontario, London, ON, Canada (E Finger PhD); and Center for Neurodegenerative Science, Van Andel Research Institute, Grand Rapids, MI, USA (R Guerreiro PhD, J Brás PhD)

Correspondence to: Dr Jonathan Rohrer, Dementia Research Centre, Department of Neurodegenerative Disease, UCL Institute of Neurology, University College London, London WC1N 3BG, UK
j.rohrer@ucl.ac.uk

For the Frontotemporal Dementia Prevention Initiative see <http://www.genfi.org.uk/fpi.html>
 For the Alzheimer Disease & Frontotemporal Dementia Mutation database see www.molgen.ua.ac.be/FTDmutations
 See Online for appendix

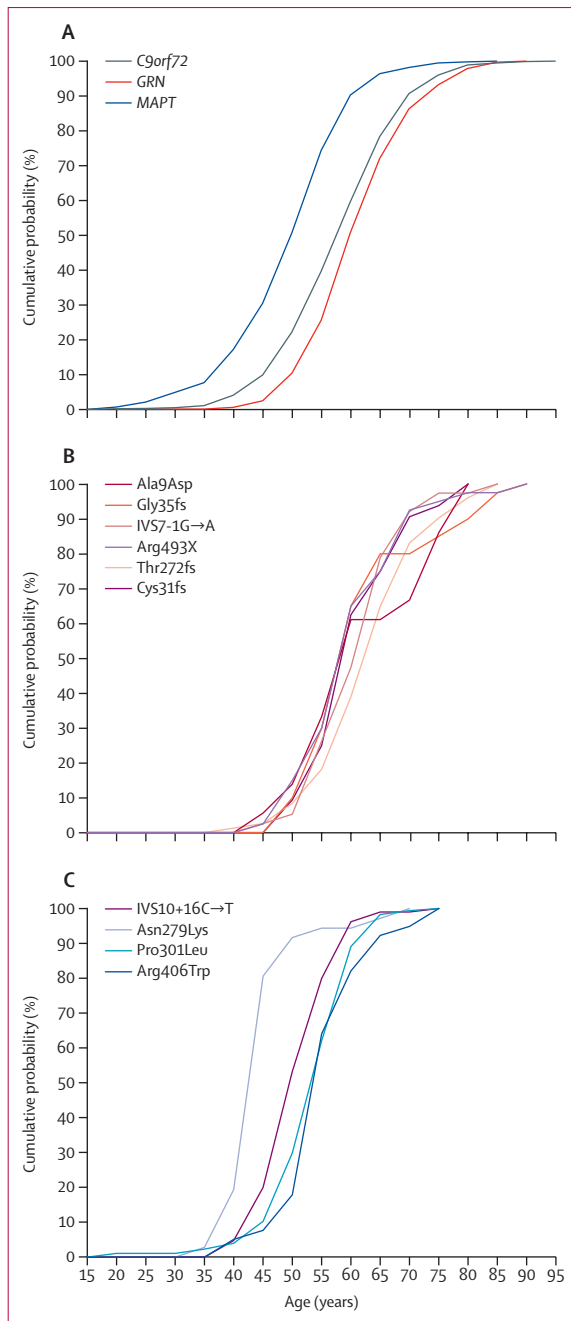


Figure 3: Cumulative probability of symptom onset for each genetic group (A) and in the common GRN (B) and MAPT (C) mutations. Data includes only individuals who have become symptomatic and does not account for family members who are not symptomatic.

nonetheless, the oldest age at symptom onset in this group was 82 years. Although usually considered a fully penetrant disorder, occasional incomplete penetrance might exist in some families with MAPT mutations (eg, Leu315Arg,¹⁰ Val363Ile,^{11,12} and Gly389Arg¹³), which might be age-related.

The investigation of individual mutations within GRN revealed little difference between them in terms of age

at symptom onset, age at death, or disease duration. These results are consistent with the underlying pathophysiological mechanism of progranulin haplo-insufficiency being the same in most GRN mutations.^{14,15} By contrast, we found significant differences between individual MAPT mutations, with the mean symptom onset in the Asn279Lys mutation group occurring 12 years earlier than in the Arg406Trp mutation group. Along with the Val337Met mutation, the Arg406Trp mutation has a distinct pathological form compared with that of the other MAPT mutations, with the presence of tau pathology with paired helical filaments similar to that seen in Alzheimer's disease; this group had a significantly longer disease duration than that of the other mutations, as previously described in single case reports.¹⁶

The generational analysis revealed significant differences in all three genetic groups, consistent with previous studies,^{4,17} with earlier age at symptom onset occurring in later (second) generations. These findings have been variably interpreted previously. One study has suggested that, in individuals with C9orf72 expansions, this finding was evidence of genetic anticipation.¹⁷ However, another research group interpreted this data as likely to be related to later generations recognising the disease earlier because of increased familiarity with symptoms and being more likely to be alert to the presence of such symptoms because of their awareness of being at-risk.⁴ At a molecular level, studies have shown that although C9orf72 expansions might be dynamic, they can both expand and contract across generations.¹⁷ Furthermore, no clear evidence exists for a relationship between age at symptom onset and expansion length, with contradictory evidence of both a positive correlation in some studies¹⁸⁻²⁰ and an inverse correlation in another.²¹ Evidence against anticipation being an explanation for the earlier age at symptom onset in later generations also comes from the similar results observed in the GRN (corroborated by another study⁴) and MAPT groups: these mutations are stable and do not change molecularly across generations, therefore no plausible mechanism exists for anticipation in GRN or MAPT mutations.

Few studies have compared whether age at symptom onset, age at death, or disease duration vary by clinical phenotype within genetic groups. In our study, individuals with a diagnosis of Alzheimer's disease within each group were significantly older at symptom onset than those with other diagnoses. Although it is possible that individuals with a true amnesic presentation of genetic frontotemporal dementia do present at an older age (and that an underlying biological explanation for this exists), this is more likely to be related to the misdiagnosis of individuals with late-onset dementia as having Alzheimer's disease. In the MAPT group, individuals with an atypical parkinsonian syndrome were significantly younger at symptom onset and at death and had a shorter disease duration than those of the other groups—this was not entirely driven by the presence of a specific mutation because the phenotype was

seen across multiple mutations (eg, only 13% of this group had an Asn279Lys mutation, which has an earlier mean age at symptom onset than that of other mutations). In the *C9orf72* group, the presence of amyotrophic lateral sclerosis was associated with a shorter disease duration than that of other phenotypes (with amyotrophic lateral sclerosis alone having a significantly shorter disease duration than the combined phenotype of frontotemporal dementia with amyotrophic lateral sclerosis), as previously reported.²² A previous study compared a combined frontotemporal dementia group with an amyotrophic lateral sclerosis group in individuals with *C9orf72* expansions and found an earlier onset in the amyotrophic lateral sclerosis group.⁹ In our *C9orf72* cohort, a significantly earlier onset was found in the amyotrophic lateral sclerosis group compared with that of a combined group of individuals with a cognitive presentation (appendix p 46), but this is partly driven by the Alzheimer's disease group and no differences were found between the amyotrophic lateral sclerosis group and either the behavioural variant frontotemporal dementia or primary progressive aphasia groups individually (appendix pp 45–46).

Individual age at symptom onset was significantly correlated with both parental age at symptom onset and mean family age at symptom onset in all three genetic groups. Similarly, individual age at death was significantly correlated with both parental age at death and mean family age at death in all three genetic groups. However, we found stronger correlations in the *MAPT* group than in the other two groups, similar to the results found in patients with familial Alzheimer's disease.²³ The variability in age at symptom onset and at death for individuals with *MAPT* mutations was partly explained by the specific mutation and more so by family membership. Unlike the other genetic groups, in the *MAPT* group, prediction of probable age at symptom onset and at death is therefore highly related to the presence of the *MAPT* mutation itself. Other genetic or environmental factors affecting age at symptom onset and at death in individuals with *MAPT* mutations have not yet been well studied.²⁴

Despite being statistically significant, correlation coefficients were low in the *GRN* group for the comparisons between individual age at symptom onset and parental and mean family age at symptom onset. The variability in age at symptom onset and age at death for individuals with *GRN* mutations was not accounted for particularly by either the individual mutation or family membership. This finding is consistent with previous reports of large variability within families (and specific mutations), even within the same generation.^{25–27} Genetic factors affecting age at symptom onset include polymorphisms in *TMEM106B*^{28,29} and potentially also in *PRNP*,³⁰ but several recent studies suggest that environmental factors related to an altered neuroinflammatory response might also be important.^{31–34}

The *C9orf72* group sits between the *GRN* and *MAPT* groups in terms of the strength of correlation of individual

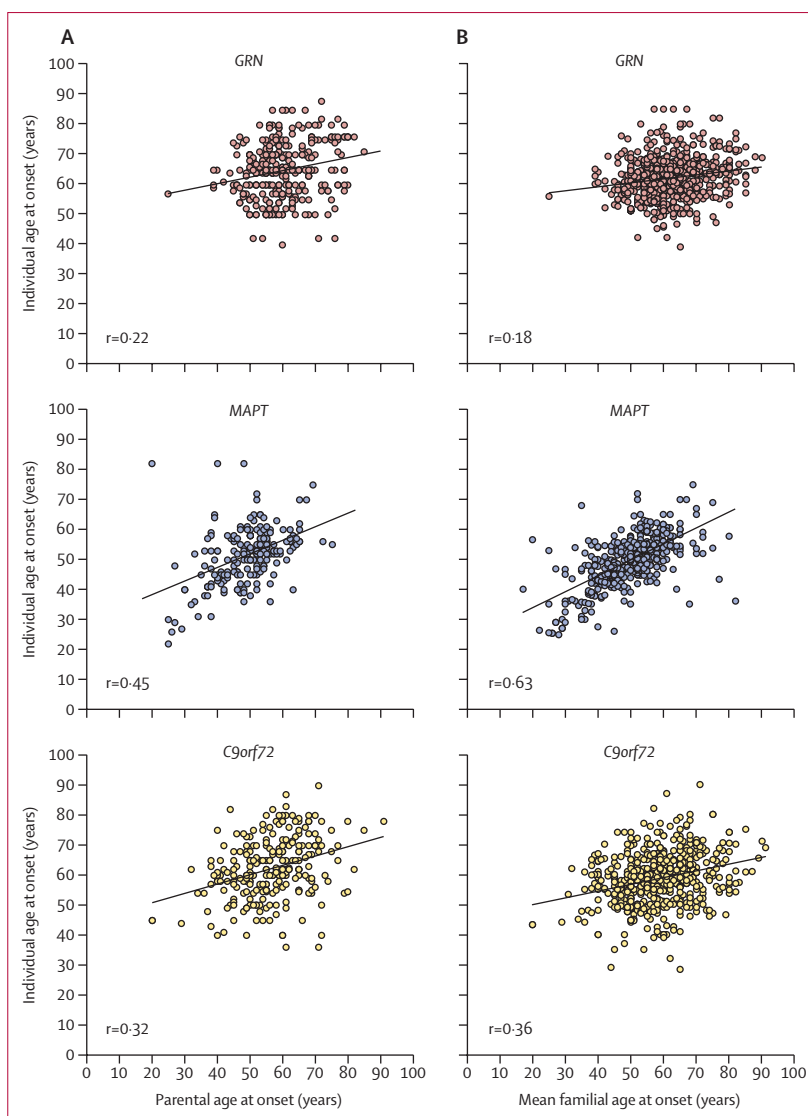


Figure 4: Correlation of individual age at symptom onset with parental (A) and mean familial (B) ages at symptom onset for *GRN*, *MAPT*, and *C9orf72* genetic groups. Pearson's correlation coefficient is shown on each graph.

age at symptom onset and at death with parental and mean family age at symptom onset and at death. However, similar to *GRN* mutations, the variability in age at symptom onset and at death was not accounted for particularly by family membership. Although conflicting evidence exists about whether expansion length is relevant,^{18–21} several studies have identified DNA methylation^{21,35,36} and a locus on chromosome 6³⁷ as important factors in age at symptom onset, age at death, and disease duration in individuals with *C9orf72* expansions (see appendix for further discussion of potential modifiers of age at symptom onset and age at death [pp 49–50]).

Our study has several limitations. One such limitation was its focus on mainly retrospective data collection, with age at symptom onset recorded as the age at which an

individual was determined to have progressive cognitive, behavioural, or motor symptoms. As such, our data might be confounded by factors such as individual differences in interpreting symptom onset. This is a major issue in the study of frontotemporal dementia, for which objective measures of symptom onset are needed. A grey zone in proximity to symptom onset exists, in which subtle cognitive and behavioural deficits are present,⁷ but have not yet been identified as symptoms by the patient themselves or family members. Work within the FPI aims to identify such proximity markers, which will be important for future stratification in clinical trials, particularly, as identified in this study, for individuals with *GRN* and *C9orf72* mutations, in whom prediction by age itself is poor.

Another limitation of the study is that we did not collect data on individuals with known mutations who did not develop symptoms of frontotemporal dementia. This is particularly important when assessing age-related penetrance in the *GRN* and *C9orf72* groups, although we did identify people older than 90 years developing symptoms of frontotemporal dementia in both these groups. Attainment of data from long-living individuals with mutations will be important to better understand the modifiers of age at symptom onset and this will require large, well characterised longitudinal cohort studies, such as those in the FPI.

Although many of the centres in our study saw patients and families with all phenotypes of frontotemporal dementia, amyotrophic lateral sclerosis, and movement disorders within their clinics, the focus on genetic frontotemporal dementia within our study might have led to an underrepresentation of patients with amyotrophic lateral sclerosis or parkinsonian disorders. However, many of the families had members with multiple different phenotypes (including cognitive, behavioural, and motor), and few families had only a single phenotype, suggesting that the data in our study is unlikely to lead to a major discrepancy in phenotypic frequency.

Lastly, we did not have any data on the *TMEM106B* genotype (which is a known modifier in individuals with *GRN* mutations) nor on other genetic modifiers, such as *APOE* genotype, to further investigate their effect. However, such data, along with various environmental and lifestyle factors, are now being collected within the FPI and will be investigated in future studies.

In summary, we showed that individuals with *MAPT* mutations are younger at symptom onset and at death than those of the other groups, with the observed variance largely accounted for by family membership and the specific mutation carried. Individuals with *GRN* mutations had the weakest association of age at symptom onset and at death with other family members, and most of the observed variance in age at symptom onset and at death was accounted for by neither family membership nor the specific mutation. However, we found a sex effect, with increased prevalence of symptomatic individuals and

older age at onset in women than in men, probably driven by age-related penetrance seen in those with *GRN* mutations. *C9orf72* expansions were the overall most common cause of genetic frontotemporal dementia in our study. Phenotypical differences in disease duration exist, with the presence of amyotrophic lateral sclerosis leading to a shortened disease duration. As in the *GRN* group, little of the variance in age at symptom onset or at death was accounted for by family membership, with other genetic and environmental factors likely to be involved.

Our study highlights the strength of collaborative studies in rare diseases, bringing together data from across the world to better understand genetic frontotemporal dementia and to provide important data relevant to future trial designs. The prospective cohort studies within the FPI will hopefully provide solutions to some of the unanswered questions over the forthcoming years.

Contributors

KMM, JDR, MG, BFB, JCVS, BCD, CG, NG, BB, DG, IRM, ALB, HR, JL, JBR, MO, MM, RLJr, CUO, and JN contributed to the study design. KMM and JDR drafted the initial version and figures. JN and JDR did the statistical analysis. All authors were involved in data collection and interpretation and drafting of the manuscript. All authors critically reviewed the manuscript and approved the final draft.

FTD Prevention Initiative collaborators

Carolyn Heller, Rhian Convery, Ione O C Woollacott, Rachele Shafei, Jonathan Graff-Radford, David T Jones, Christina M Dheel, Rodolfo Savica, Maria I Lapid, Matt Baker, Julie A Fields, Ralitza Gavrilo, Kimiko Domoto-Reilly, Jackie M Poos, Emma L van der Ende, Jessica L Panman, Laura Donker Kaat, Harro Seelaar, Anna Richardson, Giovanni Frisoni, Anna Mega, Silvia Fostinelli, Huei-Hsin Chiang, Antonella Alberici, Andrea Arighi, Chiara Fenoglio, Hilary Heuer, Bruce Miller, Anna Karydas, Jamie Fong, Maria João Leitão, Beatriz Santiago, Diana Duro, Carlos Ferreira, Alazne Gabilondo, María de Arriba, Mikel Tainta, Miren Zulaica, Catarina B Ferreira, Elisa Semler, Albert Ludolph, Bernhard Landwehrmeyer, Alexander E Volk, Gabriel Miltenberger, Ana Verdelho, Sónia Afonso, Maria Carmela Tartaglia, Morris Freedman, Ekaterina Rogava, Camilla Ferrari, Irene Piaceri, Valentina Bessi, Gemma Lombardi, Frédéric St-Onge, Marie-Claire Doré, Rose Bruffaerts, Mathieu Vandenbulcke, Jan Van den Stock, M Marsel Mesulam, Eileen Bigio, Christos Koros, John Papatriantafyllou, Christos Kroupis, Leonidas Stefanis, Christen Shoesmith, Erik Roberson, Giovanni Coppola, Eliana Marisa Da Silva Ramos, Daniel Geschwind.

Affiliations

Dementia Research Centre (C Heller MSc, R Convery MSc, I O C Woollacott MRCP, R Shafei MRCP) and UK Dementia Research Institute (C Heller), Department of Neurodegenerative Disease, Institute of Neurology, University College London, London, UK; Department of Neurology (J Graff-Radford MD, D T Jones MD, C M Dheel BSc, R Savica PhD), Department of Psychiatry (M I Lapid MD), Department of Psychology (M I Lapid, J A Fields PhD), and Department of Clinical Genomics (R Gavrilo MD), Mayo Clinic, Rochester, MN, USA; Department of Neuroscience, Mayo Clinic, Jacksonville, FL, USA (M Baker BSc); University of Washington, Seattle, WA, USA (K Domoto-Reilly MD); Department of Neurology, Erasmus Medical Centre, Rotterdam, Netherlands (J M Poos MSc, E L van der Ende MSc, J L Panman MSc, L D Kaat PhD, H Seelaar PhD); Cerebral Function Unit, Salford Royal NHS Foundation Trust and Division of Neuroscience and Experimental Psychology, University of Manchester, Manchester, UK (A Richardson MD); IRCCS Istituto Centro San Giovanni di Dio Fatebenefratelli, Brescia, Italy (G Frisoni PhD, A Mega MSc, S Fostinelli MSc); Department NVS, Center for Alzheimer Research, Division of Neurogenetics, Bioclinicum, Karolinska Institutet, Solna, Sweden (H-H Chiang MD); Unit for Hereditary Dementias, Theme Aging, Karolinska University Hospital, Solna, Sweden (H-H Chiang); Centre for

Neurodegenerative Disorders, Department of Clinical and Experimental Sciences, University of Brescia, Brescia, Italy (A Alberici PhD); Fondazione IRCCS Ca' Granda, Ospedale Maggiore Policlinico, Milan, Italy (A Arighi MD); Department of Pathophysiology and Transplantation, University of Milan, Centro Dino Ferrari, Milan, Italy (C Fenoglio PhD); Department of Neurology, Memory and Aging Center, University of California at San Francisco, San Francisco, CA, USA (H Heuer PhD, B Miller MD, A Karydas, J Fong MSc); Neurology Department, Centro Hospitalar e Universitário de Coimbra, Coimbra, Portugal (M J Leitão BSc); Faculty of Medicine, University of Coimbra, Portugal (B Santiago MD, D Duro BSc); Institute of Nuclear Sciences Applied to Health (ICNAS), Coimbra, Portugal (C Ferreira PhD); Department of Neurology, Hospital de Bidasoa, Irun, Spain (A Gabilondo MD); Neuroscience Area, Biodonostia Health Research Institute, San Sebastian, Spain (A Gabilondo, M de Arriba BSc, M Tainta MD, M Zulaica BSc); Center for Networked Biomedical Research on Neurodegenerative Disease, Carlos III Health Institute, Madrid, Spain (A Gabilondo, M de Arriba, M Tainta, M Zulaica); CITA Alzheimer, San Sebastian, Spain (M de Arriba, M Tainta); Laboratory of Neurosciences, Institute of Molecular Medicine (C B Ferreira MSc), Faculty of Medicine (G Miltenberger PhD), University of Lisbon, Lisbon, Portugal; Department of Neurology, University of Ulm, Germany (E Semler MSc, A Ludolph MD, B Landwehrmeyer MD); Institute of Human Genetics, University Medical Center Hamburg-Eppendorf, Hamburg, Germany (A E Volk MD); Department of Neurosciences and Mental Health, Centro Hospitalar Lisboa Norte, Hospital de Santa Maria and Faculty of Medicine, University of Lisbon, Lisbon, Portugal (A Verdelho PhD, S Afonso BSc); Tanz Centre for Research in Neurodegenerative Diseases, University of Toronto, Toronto, ON, Canada (M C Tartaglia PhD, E Rogoava PhD); Baycrest Health Sciences, Rotman Research Institute, University of Toronto, Toronto, ON, Canada (M Freedman MD); Department of Neuroscience, Psychology, Drug Research and Child Health, University of Florence, Florence, Italy (C Ferrari, I Piaceri, V Bessi, G Lombardi); Clinique Interdisciplinaire de Mémoire, Département des Sciences Neurologiques, Hôpital de l'Enfant-Jésus, Université Laval, Quebec, QC, Canada (F St-Onge MSc, M-C Doré PhD); Department of Neurology, University Hospitals Leuven, Leuven, Belgium (R Bruffaerts PhD, M Vandenbulcke PhD, J V den Stock PhD); Mesulam Center for Cognitive Neurology and Alzheimer's Disease, Northwestern University, Chicago, IL, USA (M M Mesulam MD, E Bigio PhD); Cognitive Disorders/Dementia Unit, 2nd Department of Neurology (C Koros MD, J Papatriantafyllou MD) and Department of Clinical Biochemistry (C Kroupis PhD), National and Kapodistrian University of Athens, Atikon University General Hospital, Athens, Greece; 1st Department of Neurology, National and Kapodistrian University of Athens, Eginition Hospital, Athens, Greece (L Stefanis MD); Department of Clinical Neurological Sciences, University of Western Ontario, London, ON, Canada (C Shoesmith MD); Departments of Neurology and Neurobiology, Center for Neurodegeneration and Experimental Therapeutics, Alzheimer's Disease Center, Evelyn F McKnight Brain Institute, University of Alabama at Birmingham, Birmingham, AL, USA (E Roberson MD); Department of Psychiatry and Semel Institute for Neuroscience and Human Behavior, David Geffen School of Medicine, University of California Los Angeles, Los Angeles, CA, USA (G Coppola PhD, E M S Ramos, D Geschwind MD).

Declaration of interests

KMM reports grants from the Alzheimer's Society, during the conduct of the study. JN reports grants from the UK Medical Research Council, during the conduct of the study. MG, CTM, and DJI report grants from the National Institutes of Health (NIH), during the conduct of the study. JDW reports grants from the Alzheimer's Society and the National Institute for Health Research (NIHR) University College London Hospitals Biomedical Research Centre, during the conduct of the study. NCF reports grants from the Leonard Wolfson Experimental Neurology Centre, and the UK Dementia Research Institute, during the conduct of the study; and personal fees from Biogen, GE Healthcare, Eli Lilly, and Roche, outside the submitted work. MNR reports fees paid to the institution from Servier and Merck, outside the submitted work. BFB reports grants from the Mayo Alzheimer's Disease Research Center and the NIH, during the conduct of the study; and personal fees from the scientific advisory board of the Tau Consortium, grants from Biogen, Mangurian Foundation, Alector, and Little Family Foundation, outside the submitted work. DSK reports

personal fees from the DIAN study and grants from Eli Lilly and Biogen, outside the submitted work. NRG-R reports grants from Novartis, AbbVie, Eli Lilly, and Biogen, outside the submitted work. JCVS reports grants from the Dioraphte Foundation, the Bluefield Project to Cure Frontotemporal Dementia, Alzheimer Nederland, ZonMw Memorabel, The Netherlands Organization for Scientific Research, and The Association for Frontotemporal Dementias Research, during the conduct of the study. LHM reports grants from Deltaplan Dementie, Alzheimer Nederland, European Joint Programme—Neurodegenerative Disease Research, the Netherlands Organisation for Health Research and Development, and the Bluefield Project, during the conduct of the study; and grants from Alector, outside the submitted work. ABri reports grants from France Parkinson and Fédération pour la Recherche sur le Cerveau, Agence Nationale de Recherche, Epigenomics of Common and Age-related Diseases, EU Joint Programme—Neurodegenerative Disease Research (JPND), Roger de Spelberch Foundation, France Alzheimer, Ecole des Neurosciences Paris, Institut de France, Centre Hospitalier Universitaire de Nîmes, ERA-NET, and Assistance Publique Hôpitaux de Paris, outside the submitted work. RGH reports grants from the Italian Ministry of Health, during the conduct of the study. BCD reports grants from the NIH National Institute of Neurological Disorders and Stroke (NIH-NINDS) during the conduct of the study. CG and LÖ report grants from the JPND Prefrontals Swedish Research council, Swedish Frontotemporal Dementia Initiative Schörling Foundation, Swedish Alzheimer foundation, Swedish Brain Foundation, and Stockholm County Council ALF, during the conduct of the study. LÖ also reports grants from Karolinska Institutet Doctoral Funding, StratNeuro, and Swedish Demensfonden, during the conduct of the study. NG reports grants from Tau Consortium and Rainwater Foundation, during the conduct of the study. JCM reports grants from the NIH, during the conduct of the study. DG and ES report grants from JPND and Italian Ministry of Health, during the conduct of the study. GGF reports grants from Associazione Italiana Ricerca Alzheimer ONLUS-COOP Italia, during the conduct of the study. IRM reports personal fees from Prevail Therapeutics, grants from Canadian Institutes of Health Research (CIHR), NIH National Institute on Aging (NIH-NIA), Brain Canada, and Weston Brain Institute, outside the submitted work; and has a patent for “Detecting and treating dementia” issued. G-YRH reports grants from CIHR, Brain Canada, and NIH-NIA. ALB reports grants from NIH-NIA and NIH-NINDS, during the conduct of the study; reports stock or options from Aeton Therapeutics and Alector; reports personal fees from Abbvie, Amgen, Arkuda, Arvinas, Denali, Ionis, Janssen, Lundbeck, Merck, Pinteon, Passage BIO, Neurogenetics, Samumed, Toyama, and UCB; and grants from C2N, Cortice, Eli Lilly, Forum, Genentech, Roche, TauRx, NIH, AFTD, Bluefield Project, Tau Consortium, outside the submitted work. GH reports grants from the National Health and Medical Research Council of Australia, during the conduct of the study. RS-V reports grants from Fundació Marató de TV3, Spain, during the conduct of the study. SB-E reports grants from the Instituto de Salud Carlos III, Spain, during the conduct of the study. FM reports grants from the Tau Consortium, during the conduct of the study. JBR reports grants from the NIHR, Wellcome Trust, and Medical Research Council, during the conduct of the study; travel funds from Guarantors of Brain; personal fees from Asceneuron, Astex, and Biogen; and grants from Janssen, AZ Medimmune, and Eli Lilly, outside the submitted work. MO and SA-S report grants from the Federal Ministry of Education and Research, Germany, during the conduct of the study. MM reports grants from the CIHR, during the conduct of the study; is part of the editorial board of Current Pharmacogenomics and Personalized Medicine; personal fees from Arkuda Therapeutics and Ionis; and grants from the CIHR, Early Researcher Award, Ministry of Economic Development and Innovation of Ontario, Ontario Brain Institute, Sunnybrook AFP Innovation Fund, Alzheimer's Drug Discovery Foundation, Brain Canada, Heart and Stroke Foundation Centre for Stroke Recovery, Weston Brain Institute, Roche, Washington University, Axovant, Novartis, and Alector; and reports royalties from Henry Stewart Talks, outside the submitted work. SEB reports grants and personal fees from Eli Lilly, Novartis, Biogen Idec, and Roche; and grants from GE Healthcare, Genentech, and Optina, outside the submitted work. EDH reports grants from the NIH-NINDS, outside the submitted work. RV reports grants from the Mady Browaeys Fund for Research into Frontotemporal Dementia, during the conduct of the study. PVD reports membership of advisory board for Pfizer,

Cytokinetics, and Alexion Pharmaceuticals, outside the submitted work. EJR reports grants from the NIH, during the conduct of the study. SW reports grants from the NIH, during the conduct of the study, and consulting fees from Bracket Global, outside the submitted work. CUO reports grants from the NIH, and support for research from the Jane Tanger Black Scholarship, the Nancy H Hall Memorial Fund, and the Joseph Trovato Fund, during the conduct of the study; and reports a grant from Biogen, outside the submitted work. ASLN reports grants from the National Medical Research Council Singapore, during the conduct of the study. EF reports grants from the CIHR, during the conduct of the study. JDR reports grants from the UK Medical Research Council, the NIHR Rare Diseases Translational Research Collaboration, the Bluefield Project, and the Association for Frontotemporal Degeneration, during the conduct of the study; and was on the medical advisory boards for Ionis, Alector, and Prevail, outside the submitted work. MF reports an International Patent Application (PCT/CA2009/000346) and an Israeli Patent Application (208134) pending. All other authors declare no competing interests.

Acknowledgments

We particularly extend our appreciation to the patients and their families who have been active participants in genetic frontotemporal dementia research for over three decades.

Editorial note: the *Lancet* Group takes a neutral position with respect to territorial claims in published maps and institutional affiliations.

References

- Warren JD, Rohrer JD, Rossor MN. Clinical review. Frontotemporal dementia. *BMJ* 2013; **347**: f4827.
- Harris JM, Gall C, Thompson JC, et al. Classification and pathology of primary progressive aphasia. *Neurology* 2013; **81**: 1832–39.
- Rohrer JD, Guerreiro R, Vandrovicova J, et al. The heritability and genetics of frontotemporal lobar degeneration. *Neurology* 2009; **73**: 1451–56.
- Barbier M, Camuzat A, Houot M, et al. Factors influencing the age at onset in familial frontotemporal lobar dementia: important weight of genetics. *Neurol Genet* 2017; **3**: e203.
- Cosseddu M, Benussi A, Gazzina S, et al. Mendelian forms of disease and age at onset affect survival in frontotemporal dementia. *Amyotroph Lateral Scler Frontotemporal Degener* 2018; **19**: 87–92.
- Ferrari R, Grassi M, Graziano F, et al. Effects of multiple genetic loci on age at onset in frontotemporal dementia. *J Alzheimers Dis* 2017; **56**: 1271–78.
- Rohrer JD, Nicholas JM, Cash DM, et al. Presymptomatic cognitive and neuroanatomical changes in genetic frontotemporal dementia in the Genetic Frontotemporal Dementia Initiative (GENFI) study: a cross-sectional analysis. *Lancet Neurol* 2015; **14**: 253–62.
- Gass J, Cannon A, Mackenzie IR, et al. Mutations in progranulin are a major cause of ubiquitin-positive frontotemporal lobar degeneration. *Hum Mol Genet* 2006; **15**: 2988–3001.
- Murphy NA, Arthur KC, Tienari PJ, Houlden H, Chiò A, Traynor BJ. Age-related penetrance of the *C9orf72* repeat expansion. *Sci Rep* 2017; **7**: 2116.
- van Herpen E, Rosso SM, Serverijnen LA, et al. Variable phenotypic expression and extensive tau pathology in two families with the novel tau mutation L315R. *Ann Neurol* 2003; **54**: 573–81.
- Anfossi M, Bernardi L, Gallo M, et al. *MAPT* V363I variation in a sporadic case of frontotemporal dementia: variable penetrant mutation or rare polymorphism? *Alzheimer Dis Assoc Disord* 2011; **25**: 96–99.
- Munoz DG, Ros R, Fatas M, Bermejo F, de Yébenes JG. Progressive nonfluent aphasia associated with a new mutation V363I in tau gene. *Am J Alzheimers Dis Other Dement* 2007; **22**: 294–99.
- Rossi G, Marelli C, Farina L, et al. The G389R mutation in the *MAPT* gene presenting as sporadic corticobasal syndrome. *Mov Disord* 2008; **23**: 892–95.
- Baker M, Mackenzie IR, Pickering-Brown SM, et al. Mutations in progranulin cause tau-negative frontotemporal dementia linked to chromosome 17. *Nature* 2006; **442**: 916–19.
- Cruts M, Gijselinck I, van der Zee J, et al. Null mutations in progranulin cause ubiquitin-positive frontotemporal dementia linked to chromosome 17q21. *Nature* 2006; **442**: 920–24.
- Ygländ E, van Westen D, Englund E, et al. Slowly progressive dementia caused by *MAPT* R406W mutations: longitudinal report on a new kindred and systematic review. *Alzheimers Res Ther* 2018; **10**: 2.
- Van Mossevelde S, van der Zee J, Gijselinck I, et al. Clinical evidence of disease anticipation in families segregating a *C9orf72* repeat expansion. *JAMA Neurol* 2017; **74**: 445–52.
- van Blitterswijk M, DeJesus-Hernandez M, Niemantsverdriet E, et al. Association between repeat sizes and clinical and pathological characteristics in carriers of *C9ORF72* repeat expansions (Xpansize-72): a cross-sectional cohort study. *Lancet Neurol* 2013; **12**: 978–88.
- Nordin A, Akimoto C, Wuolikainen A, et al. Extensive size variability of the GGGGCC expansion in *C9orf72* in both neuronal and non-neuronal tissues in 18 patients with ALS or FTD. *Hum Mol Genet* 2015; **24**: 3133–42.
- Fournier C, Barbier M, Camuzat A, et al. Relations between *C9orf72* expansion size in blood, age at onset, age at collection and transmission across generations in patients and presymptomatic carriers. *Neurobiol Aging* 2019; **74**: 234.e1–8.
- Gijselinck I, Van Mossevelde S, van der Zee J, et al. The *C9orf72* repeat size correlates with onset age of disease, DNA methylation and transcriptional downregulation of the promoter. *Mol Psychiatry* 2016; **21**: 1112–24.
- Irwin DJ, McMillan CT, Brettschneider J, et al. Cognitive decline and reduced survival in *C9orf72* expansion frontotemporal degeneration and amyotrophic lateral sclerosis. *J Neurol Neurosurg Psychiatry* 2013; **84**: 163–69.
- Ryman DC, Acosta-Baena N, Aisen PS, et al. Symptom onset in autosomal dominant Alzheimer disease: a systematic review and meta-analysis. *Neurology* 2014; **83**: 253–60.
- Koriath C, Lashley T, Taylor W, et al. ApoE4 lowers age at onset in patients with frontotemporal dementia and tauopathy independent of amyloid- β copathology. *Alzheimers Dement* 2019; **11**: 277–80.
- Kelley BJ, Haidar W, Boeve BF, et al. Prominent phenotypic variability associated with mutations in Progranulin. *Neurobiol Aging* 2009; **30**: 739–51.
- Beck J, Rohrer JD, Campbell T, et al. A distinct clinical, neuropsychological and radiological phenotype is associated with progranulin gene mutations in a large UK series. *Brain* 2008; **131**: 706–20.
- Le Ber I, Camuzat A, Hannequin D, et al. Phenotype variability in progranulin mutation carriers: a clinical, neuropsychological, imaging and genetic study. *Brain* 2008; **131**: 732–46.
- Nicholson AM, Rademakers R. What we know about TMEM106B in neurodegeneration. *Acta Neuropathol* 2016; **132**: 639–51.
- Pottier C, Zhou X, Perkerson RB 3rd, et al. Potential genetic modifiers of disease risk and age at onset in patients with frontotemporal lobar degeneration and *GRN* mutations: a genome-wide association study. *Lancet Neurol* 2018; **17**: 548–58.
- Moreno F, Alzualde A, Cambor PM, et al. Prion protein codon 129 polymorphism modifies age at onset of frontotemporal dementia with the C.709-1G>A progranulin mutation. *Alzheimer Dis Assoc Disord* 2011; **25**: 93–95.
- Bossù P, Salani F, Alberici A, et al. Loss of function mutations in the progranulin gene are related to pro-inflammatory cytokine dysregulation in frontotemporal lobar degeneration patients. *J Neuroinflammation* 2011; **8**: 65.
- Martens LH, Zhang J, Barmada SJ, et al. Progranulin deficiency promotes neuroinflammation and neuron loss following toxin-induced injury. *J Clin Invest* 2012; **122**: 3955–59.
- Miller ZA, Rankin KP, Graff-Radford NR, et al. TDP-43 frontotemporal lobar degeneration and autoimmune disease. *J Neurol Neurosurg Psychiatry* 2013; **84**: 956–62.
- Menzel L, Kleber L, Friedrich C, et al. Progranulin protects against exaggerated axonal injury and astrogliosis following traumatic brain injury. *Glia* 2017; **65**: 278–92.
- Russ J, Liu EY, Wu K, et al. Hypermethylation of repeat expanded *C9orf72* is a clinical and molecular disease modifier. *Acta Neuropathol* 2015; **129**: 39–52.
- Zhang M, Tartaglia MC, Moreno D, et al. DNA methylation age-acceleration is associated with disease duration and age at onset in *C9orf72* patients. *Acta Neuropathol* 2017; **134**: 271–79.
- Zhang M, Ferrari R, Tartaglia MC, et al. A C6orf10/LOC101929163 locus is associated with age of onset in *C9orf72* carriers. *Brain* 2018; **141**: 2895–907.