Genetics of frontotemporal lobar degeneration

Daniela Galimberti1,2* and Elio Scarpini1,2

1 Department of Neurological Sciences, “Dino Ferrari” Center, University of Milan, Milan, Italy
2 Fondazione Cà Granda, IRCCS Ospedale Maggiore Policlinico, Milan, Italy

Edited by:
João Massano, Centro Hospitalar de São João and University of Porto, Portugal
Reviewed by:
Leone E. Rojo, Rutgers University, USA
Jonathan Rohrer, University College London, UK
*Correspondence:
Daniela Galimberti, Department of Neurological Sciences, “Dino Ferrari” Center, University of Milan, Via F. Sforza 35, 20122 Milan, Italy; Fondazione Cà Granda, IRCCS Ospedale Maggiore Policlinico, Via F. Sforza 35, 20122 Milan, Italy. e-mail: daniela.galimberti@unimi.it

NEW DIAGNOSTIC CRITERIA OF FRONTOTEMPORAL LOBAR DEGENERATION

Frontotemporal lobar degeneration (FTLD), the most frequent neurodegenerative disorder with a presenile onset, presents with a spectrum of clinical manifestations, ranging from behavioral and executive impairment to language disorders and motor dysfunction. Familial aggregation is frequently reported, and about 10% of cases have an autosomal dominant transmission. Microtubule associated protein tau (MAPT) gene mutations have been the first ones identified and are associated with early onset behavioral variant frontotemporal dementia phenotype. More recently, progranulin gene (GRN) mutations were recognized in association with familial form of FTLD. In addition, other genes are linked to rare cases of familial FTLD. Lastly, a number of genetic risk factors for sporadic forms have also been identified. In this review, current knowledge about mutations at the basis of familial FTLD will be described, together with genetic risk factors influencing the susceptibility to FTLD.

Keywords: genetics, frontotemporal lobar degeneration, autosomal dominant, mutation, risk factor

Frontotemporal lobar degeneration (FTLD), the most frequent neurodegenerative disorder with a presenile onset, presents with a spectrum of clinical manifestations, ranging from behavioral and executive impairment to language disorders and motor dysfunction. Familial aggregation is frequently reported, and about 10% of cases have an autosomal dominant transmission. Microtubule associated protein tau (MAPT) gene mutations have been the first ones identified and are associated with early onset behavioral variant frontotemporal dementia phenotype. More recently, progranulin gene (GRN) mutations were recognized in association with familial form of FTLD. In addition, other genes are linked to rare cases of familial FTLD. Lastly, a number of genetic risk factors for sporadic forms have also been identified. In this review, current knowledge about mutations at the basis of familial FTLD will be described, together with genetic risk factors influencing the susceptibility to FTLD.

For the demonstration of an autosomal dominant mutation is necessary the presence of familial aggregation and the autosomal dominant transmission of the disease suggested so far a genetic cause (Snowden et al., 2002; Bird et al., 2003; Goldman et al., 2005). Up to 40% of patients have a family history suggesting FTLD in at least one extra family member (Goldman et al., 2005; Pickering-Brown, 2007), with a percentage of autosomal dominant cases accounting for 13.4% of the total (Goldman et al., 2005).

NEW DIAGNOSTIC CRITERIA OF FRONTOTEMPORAL LOBAR DEGENERATION

Frontotemporal lobar degeneration (FTLD) represents a common cause of dementia in subjects under 65 years. The age at onset is typically 45–65 years, with a mean average in the 50s, and the prevalence is equal among men and women. It is associated with frontal and temporal lobe atrophy, involving the right and left hemispheres, in some cases asymmetrically (Rosen et al., 2006). It can be classified into two main cognitive syndromes (Neary et al., 1998): behavioral variant frontotemporal dementia (bvFTD) and primary progressive aphasia (PPA), whose diagnostic criteria have been recently revised including neuroimaging and genetics (Gorno-Tempini et al., 2011; Rascovsky et al., 2011).

Behavioral variant frontotemporal dementia is the most frequent FTLD phenotype, characterized by behavioral alterations, such as disinhibition, overeating, and impulsiveness, and impairment of cognitive functions, with relative sparing of memory (Hou et al., 2004). Changes in social behavior, loss of empathy, and impairment of social insight are early and consistent symptoms of bvFTD, whose importance and role for the early diagnosis has been emphasized in the new consensus criteria (Rascovsky et al., 2011). According to these criteria, bvFTD main feature is the progressive deterioration of behavior and/or cognition by observation or history. If this criterion is satisfied, there are three further levels of certainty for bvFTD: possible, probable, or definite. “Possible” bvFTD requires three out of six clinically discriminating features (disinhibition, apathy/inertia, loss of sympathy/empathy, perseverative/compulsive behaviors, hyperorality, and dysexecutive neuropsychological profile). “Probable” bvFTD meets the criteria of “possible” bvFTD plus (1) a significant functional decline (by caregiver report or evidenced at neuropsychological testing) (2) frontal and/or anterior temporal atrophy on MRI or CT, or frontal and/or anterior temporal hypoperfusion or hypometabolism on PET or SPECT. “Definite” bvFTD imply the histopathological evidence of FTLD on biopsy or post mortem or the presence of a known pathogenic mutation. These new criteria have a flexible structure to account for the high heterogeneity at initial presentation.

Early and progressive changes in language functions represent the alternative presentation of FTLD. Progressive loss of speech, with hesitant, non-fluent speech output with phonetic/phonological errors, and distortions and/or agrammatism is typical of primary non-fluent aphasia (PNFA) subtype (Scarpini et al., 2006), whereas loss of knowledge about words and objects, anoma and single-word comprehension deficits are core features of the semantic variant of PPA, named semantic dementia (SD; Gorno-Tempini et al., 2011). A third subtype of PPA has been recently described as logopenic or phonological variant (LPA). It is characterized by phonological disorders, defective word retrieval, and sentence repetition deficits. This PPA subtype seems to be associated with underlying Alzheimer’s disease (AD) pathology (Rabinovici et al., 2008).

GENETICS: AUTOSOMAL DOMINANT MUTATIONS

The presence of familial aggregation and the autosomal dominant transmission of the disease suggested so far a genetic cause (Snowden et al., 2002; Bird et al., 2003; Goldman et al., 2005). Up to 40% of patients have a family history suggesting FTLD in at least one extra family member (Goldman et al., 2005; Pickering-Brown, 2007), with a percentage of autosomal dominant cases accounting for 13.4% of the total (Goldman et al., 2005).

New criteria for bvFTD diagnosis (Rascovsky et al., 2011) include the presence of a known mutation as a biomarker. The demonstration of an autosomal dominant mutation is
After the discovery of MAPT as causal gene for FTDP-17, there were still numerous autosomal dominant FTLD cases genetically linked to the same chromosomal region of MAPT (chr17q21), in which no pathogenic mutations had been identified. A small region rich of genes, localized approximately 6.2 Mb in physical distance to MAPT locus, had been recognized as that one containing the gene responsible for the disease in these families. Systematic sequencing of candidate genes within this minimal region was performed and the first mutation in progranulin gene (GRN) was identified. It consists of a 4-bp insertion of CTGC between coding nucleotides 90 and 91, causing a frameshift and premature termination in progranulin (C31LfsX34; Baker et al., 2006). Cruts et al. (2006), analyzing other families with a FTLD pathology without MAPT mutation, found at the same time another mutation of five base pairs into the intron following the first non-coding exon of the gene (IVS0 + 5G–C). This mutation causes the splicing out of the intron 0, leading the retention of mRNA within the nucleus and its degradation.

GRN gene encodes for the growth regulation factor progranulin, belonging to a family of proteins involved in many biological functions including development, wound repair, and inflammation by activating signaling cascades that control cell cycle progression (He and Bateman, 2003). Progranulin is a 593 amino acid protein, rich of cysteine with a molecular weight of 68.5 kDa, subjected to proteolysis by elastase in a process regulated by a secretory leukocyte protease inhibitor (SLPI; Zhu et al., 2002). It is expressed not only in neurons but also is the activated microglia (Baker et al., 2006).

Since the original identification of null-mutations in FTLD in 2006, 69 different mutations have been described so far (http://www.molgen.ua.ac.be/) in 231 families. Most of the known pathogenic GRN mutations, including frameshift, splice-site, and nonsense mutations, are predicted to result in a premature stop codon. The resulting aberrant mRNA is degraded through the process of nonsense mediated decay, leading to haploinsufficiency (Gass et al., 2006).

Clinically, mutations in GRN are associated with extremely heterogeneous phenotypes, including, besides the classical FTLD presentations, AD (Carecchio et al., 2009), corticobasal syndrome (CBS; Carecchio et al., 2011), or Mild Cognitive Impairment (Pietroboni et al., 2011). Age at disease onset is extremely wide, even in the same family (Pietroboni et al., 2011). In addition, the demonstration of the clinical overlap between psychiatric disorders and genetically determined FTLD comes from the recent description of a patient with heterosexual pedophilia (Rainero et al., 2011), who was a carrier of a GRN mutation and developed bvFTD over time, and from a second description reporting two clinically different, apparently sporadic FTLD cases sharing the previously described Thr272fs GRN mutation, who had had a premorbid bipolar disorder history (Cerami et al., 2011).

A major contribution to achieve a correct diagnosis independent of the phenotypic presentation is the demonstration that progranulin plasma levels are extremely low in GRN mutation carriers, even in asymptomatic subjects (Ghidoni et al., 2008; Finch et al., 2009; Carecchio et al., 2011; Pietroboni et al., 2011).

Notwithstanding the striking proximity of MAPT and GRN on chromosome 17, at this time, there is no clear link between these two genes, suggesting that their closeness is just a coincidence.

GRN-mutated FTLD cases at the neuropathological examination presented ubiquitin immunoreactive cytoplasmic and intranuclear neuronal inclusions similar to the microvacuolar type still observed in a large proportion of apparently sporadic FTLD, and differing from the tau-positive inclusions typical of MAPT mutated cases. Soon after the identification of GRN mutation, truncated, and hyperphosphorylated isoforms of the TAR–DNA binding protein (TDP)–43 were recognized as main components of the ubiquitin-positive inclusions typical of the GRN-mutated families, as well as of idiopathic FTLD and of a proportion of amyotrophic lateral sclerosis (ALS) cases (Neumann et al., 2006).
GRN mutations account for about 5–10% of all FTD cases, markedly varying depending on the population considered (Cruts et al., 2006; Gass et al., 2006; Snowden et al., 2006). A collaborative study (Yu et al., 2010) analyzing GRN mutations in 434 FTLD patients, clinically ranging from bvFTD to PNFA, FTLD associated with parkinsonism or MND, estimates a frequency of 6.9% of all included FTLD-spectrum cases. In these cases, the 56.2% was represented by FTLD-U-diagnosed subjects with a known familial history of FTD, pathologically confirmed. Clinical information were available for 31 GRN mutation-positive patients: the most common phenotype was bvFTD (n = 24), while 3 patients were diagnosed with PNFA, 3 with AD, and 1 with CBS (Yu et al., 2010).

CHROMATIN-MODIFYING 2B
Few FTLD families display mutations in the CHMP2B gene, which encodes a component of the heteromeric endosomal sorting complex required for transport (ESCRT III complex) involved in the endosomal trafficking and degradation (Skibinski et al., 2005). To date, only four different mutations between or in the exons 5 and 6 have been so far described in five families (http://www.molgen.ua.ac.be/), making CHMP2B an extremely rare genetic cause of FTLD pathology. Neuropathologically, patients with CHMP2B mutations present FTLD-U with ubiquitin-positive but TDP-43-negative cytoplasmic inclusions (Holm et al., 2007). Behavioral and cognitive impairment associated with extrapyramidal and pyramidal signs are the main clinical manifestations in CHMP2B mutation carriers. Myoclonus can occur late in the course of the disease (Gydesen et al., 2002) and motor neuron disorders have been described in only two cases (Parkinson et al., 2006).

VALOSIN-CONTAINING PROTEIN-1
Some familial cases having mutations in the VCP-1 gene were reported (Watts et al., 2004). However, the phenotype associated with such mutations is inclusion body myopathy, Paget’s disease of bone and less frequently FTLD (IBMPFD; Kimonis et al., 2008). Myopathy is the more frequent clinical symptom, present in about 90% of affected subjects, whereas FTD is seen in about 30%, usually many years after the onset of muscle symptoms.

TARDBP
The most common clinical phenotype associated with TARDBP mutations is ALS, and aggregates made of TDP-43 have been described in brain and spinal cord of such patients. Nevertheless, TARDBP mutated subjects can present also parkinsonism in association with motor neuron dysfunction (see Pesiridis et al., 2009 for review). At present, TARDBP mutations have been found in 5% of familial ALS and only rarely in FTD and FTLD–MND subjects (Benajiba et al., 2009; Borroni et al., 2009).

Chr 9 HEXANUCLEOTIDE REPEITION
Lastly, one of the most intriguing discovery in the genetics of FTLD has been the investigation of FTD/MND families linked to a locus on chromosome 9q21–22. The first evidence of linkage with this locus comes from a study carried out in families with FTD–MND (Hosler et al., 2000). After some others reports confirming the linkage to chr9q21–22 in additional FTD–MND families (Morita et al., 2006; Rollinson et al., 2011), and a search lasting more than a decade, in 2011, two groups of researchers identified the gene responsible for the disease, the chromosome 9 open reading frame 72 (C9ORF72). Both these studies (Dejesus-Hernandez et al., 2011; Renton et al., 2011) reported a large hexanucleotide (GGGGCC) repeat expansion in the first intron of C9ORF72 as responsible for a high number of familiar ALS or combined FTD–MND phenotype and TDP-43 based pathology. This mutation causes the loss of one alternatively spliced transcript, whose function is still unknown, and the formation of nuclear RNA foci. Wild-type alleles contain no more than 23–30 repeats, whereas mutated alleles have more than 100 repeats. These studies thus demonstrated that C9ORF72 mutation is at present a major cause of both familial FTD (12%) and ALS (22.5%) cases (Dejesus-Hernandez et al., 2011), with a higher prevalence in the northern population, reaching a prevalence of 46% of all familiar ALS, 21.1% of sporadic ALS, and 29.3% of FTD in the Finnish population (Renton et al., 2011). Clinically, the large clinical series reported in these studies show that the predominant phenotypes are consistent with bvFTD and ALS, with different phenotypic presentation even in the same family (i.e., FTD, ALS, or a combination of both). From the FTLD series reported in Dejesus-Hernandez et al. (2011) study, 26.9% FTLD cases had concomitant ALS and more than 30% had relatives affected with ALS.

CONCLUSIVE REMARKS
In the last few years, it has become clear that there are multiple genetic autosomal dominant mutations leading to the development of FTLD. The most frequent are so far MAPT and GRN mutations that are associated with high phenotypic variability. Whereas the majority of MAPT mutations is characterized by an early onset of symptoms and is associated with a clear segregation across generations, age at disease onset is very wide in GRN mutation carriers. According to the most recent discoveries, the large hexanucleotide (GGGGCC) repeat expansion in the first intron of C9ORF72 is not only one of the most frequent mutation associated with ALS and FTLD–MND, but is also the second most frequent in FTLD, after GRN mutations (Gijselinck et al., 2012). Given the incomplete penetrance of such mutations, a number of cases are apparently sporadic, making more difficult to suspect the presence of a causal mutation. Regarding genetic counseling, at present no international shared guidelines are available.

GENETICS: RISK FACTORS
The first candidate-gene studied in FTLD was the well-known risk factor for late onset sporadic AD, APOE. A number of studies suggested an association between FTLD and APOE4 allele (Farrer et al., 1995; Helsalimi et al., 1996; Gustafsson et al., 1997; Stevens et al., 1997; Fabre et al., 2001; Bernardi et al., 2006). Nevertheless, other authors did not replicate these data (Geschwind et al., 1998; Riemenschneider et al., 2002; Short et al., 2002). Additional findings demonstrated an association between the APOE4 allele and FTLD in males, but not females (Srinivasan et al., 2006). An increased frequency of the APOE4 allele has been described in patients with SD compared to those with FTD and PNFA (Short et al., 2002).
Concerning the APOE*2 allele, Bernardi et al. (2006) showed a protective effect of this allele toward FTLD, whereas other authors failed to do so (Riemenschneider et al., 2002; Short et al., 2002; Engelborghs et al., 2003; Srinivasan et al., 2006). A meta-analysis comprising a total of 364 FTD patients and 2671 controls demonstrated an increased susceptibility to FTD in APOE*2 carriers (Verpillat et al., 2002).

Besides pathogenic mutations, several polymorphisms have been described both in MAPT and GRN. In Baker et al. (1999), two common MAPT haplotypes, named H1 and H2, were identified. They differ in nucleotide sequence and intron size, but are identical at the amino acid level. Homozygosis of the more common allele H1 predisposes to Progressive Supranuclear Palsy and CBS, but not to AD or Pick Disease (Baker et al., 1999; Di Maria et al., 2000).

A contribution of GRN genetic variability in sporadic FTLD has previously been shown (Rademaker et al., 2008), even though another study did not confirm these data (Rollinson et al., 2011). A further association analysis demonstrated that a single nucleotide polymorphism (SNP) in the GRN promoter influences the risk for FTLD (Galimberti et al., 2010).

A known polymorphism (A-2518G) in monocyte chemoattractant-1 (MCP-1) gene has been shown to exert a protective effects toward the development of FTLD (Galimberti et al., 2009), whereas Nitric Oxide Synthase (NOS)3 G894T (Glu298Asp) and NOS1 C276T SNPs likely increase the risk to develop FTLD (Venturelli et al., 2008, 2009). Further genetic risk factors, discovered on a candidate-gene basis, include BCL2-associated athanogene 1 (BAG1), an anti-apoptotic factor that interacts with tau and regulates its proteasomal degradation (Venturelli et al., 2011), KIF24 (Venturelli et al., 2010), and defective in cullin neddylation 1 (DCUN1D1) domain containing 1 (DCUN1D1) whose variants may increase the risk to develop the disease by increasing GRN gene expression.

This association was confirmed in an independent Flanders–Belgian cohort of FTLD patients (n = 288; van der Zee et al., 2011). However, these findings were not confirmed by replication study performed in two clinical FTLD cohorts of British origin (Rollinson et al., 2011). Though these authors failed to detect any association of TMEM106B, the analysis of chromosome 9 locus revealed strong association in the London FTLD cohort and in the FTLD/ALS cases of the Manchester cohort, later confirmed with the discovery of the C9ORF72 gene (Dejesus-Hernandez et al., 2011; Renton et al., 2011).

REFERENCES

Baker, M., Litvan, I., Houlden, H., Adamson, J., Dickson, D., Perez-Tur, J., Hardy, J., Lynch, T., Bigio, E., and Hutton, M. (1999). Association of an extended haplotype in the tau gene with progressive supranuclear palsy. Hum. Mol. Genet. 8, 711–715.

Baker, M., Mackenzie, I. R., Pickering-Brown, S. M., Gass, J., Rademaker, R., Lindholm, C., Snowden, J., Adamson, J., Sadownik, A. D., Rollinson, S., Cannon, A., Dwosh, E., Neary, D., Meqlquit, S., Richardson, A., Dickson, D., Berger, Z., Eriksen, J., Robinson, T., Zehr, C., Dickey, C. A., Crook, R., McGowan, E., Mann, D., Boeve, B., Feldman, H., and Hutton, M. (2006). Mutations in progranulin cause tau-negative frontotemporal dementia linked to chromosome 17. Nature 442, 916–919.

Benajiba, L., Le Ber, I., Camuzat, A., Lacoste, M., Thomas-Anterion, C., Courratier, P., Legallic, S., Salachas, F., Hannequin, D., Decousus, M., Lacomblez, L., Guedj, E., Golfer, V., Camu, W., Dubois, B., Campond, D., Meiningier, V., Brice, A., and French Clinical and Genetic Research Network on Frontotemporal Lobar Degeneration/ Frontotemporal Lobar Degeneration with Motor Neuron Disease. (2009). TARDDBP mutations in motor neuron disease with frontotemporal lobar degeneration. Ann. Neurol. 65, 470–473.

Bernardi, L., Maletta, R. G., Tomaino, C., Smirne, N., Di Natale, M., Perri, M., Longo, T., Colao, R., Curcio, S. A., Puccio, G., Mirabelli, M., Kawarai, T., Rogaeva, E., St George Hyslop, P. H., Passarino, G., de Benedictis, G., and Bruni, A. C. (2006). The effects of APOE and tau gene variability on risk of frontotemporal dementia. Neurobiol. Aging 27, 702–709.

Bird, T., Knopman, D., Van Swieten, J., Rosso, S., Feldman, H., Tanabe, H., Graff-Radford, N., Geschwind, D., Verpillat, P., and Hutton, M. (2003). Epidemiology and genetics of frontotemporal dementia/Pick’s disease. Ann. Neurol. 54, S29–S31.

Borroni, B., Bonvicini, C., Alberici, A., Buratti, E., Agosti, C., Archetti, S., Papetti, A., Stuani, C., Di Luca, M., Gennarelli, M., and Padovani, A. (2009). Mutations in GRN lead to frontotemporal dementia with null mutations in progranulin cause tau-negative frontotemporal dementia linked to chromosome 17. Nature 442, 916–919.

Carcenica, M., Fenoglio, C., Cortini, F., Comi, C., Benussi, L., Ghidoni, R., Borroni, B., De Riu, M., Serpente, M., Cantoni, C., Franceschi, M., Albertini, V., Monaco, E., Rainiero, L., Binetti, G., Padovani, A., Bressolin, N., Scarpini, E., and Galimberti, D. (2011). Cerebrospinal fluid biomarkers in progranulin mutations carriers. J. Alzheimers Dis. 27, 781–790.

Carcenica, M., Fenoglio, C., De Riu, M., Guidi, I., Comi, C., Corini, F., Venturelli, E., Restelli, I., Cantoni, C., Bressolin, N., Monaco, F., Scarpini, E., and Galimberti, D. (2009). Progranulin plasma levels as potential biomarker for the identification of GRN deletion carriers. A case with atypical onset as clinical amnestic mild cognitive impairment converted to Alzheimer’s disease. J. Neurol. Sci. 287, 291–293.

Cerami, C., Marcone, A., Galimberti, D., Villa, C., Scarpini, E., and Cappa, S. F. (2011). From genotype to phenotype: two cases of genetic frontotemporal lobar degeneration with premorbid bipolar disorder. J. Alzheimers Dis. 27, 791–797.

Cruts, M., Gijselinck, I., van der Zee, J., Engelborghs, S., Wils, H., Piciri, D., Rademakers, R., Vandenbergh, R., Dermaut, B., Martin, J. J., van Duijn, C., Peeters, K., Sciort, R., Santens, P., De Pooter, T., Mattheijssens, M., Van den Broeck, M., Cuijt, I., Vennekens, K., De Dep, P. K., Kumar-Singh, S., and van Broeckhoven, C. (2006). Null mutations in progranulin cause ubiquitin-positive frontotemporal dementia linked to chromosome 17q21. Nature 442, 920–924.

Dejesus-Hernandez, M., Mackenzie, I. R., Boeve, B. F., Boxer, A. L., Baker, M., Rutherford, N. J., Nicholson, A. M., Finch, N. A., Flynn, H., Adams, J., Kouri, N., Wijjas, A., Sengyl, A., Hsiung, G. Y., Karydas, A., Sisley, W. W., Jospehs, K. A., Coppola, G., Geschwind, D. H., Wszolek, Z. K., Feldman, H., Knopman, D. S., Petersen, R. C., Miller, B. L., Dickson, D. W., Boylan, K. B., Graff-Radford, N. R., and Rademakers, R. (2011). Expanded GGGGCC hexanucleotide repeat in noncoding region of C9ORF72 causes chromosome 9p-linked FTD and ALS. Nature 472, 245–256.

Di Maria, E., Tabatton, M., Vigo, T., Abbuzzesee, G., Bellone, E., Donati, C., Frasson, E., Marchese, R., Montagna, P., Munoz, D. G., Pramstaller, P. P., Zansuso, A., Ajmar, F., and Mandich, P. (2000). Corticobasal degeneration shares a common genetic background with progressive supranuclear palsy. Ann. Neurol. 47, 374–377.
Engelborghs, S., Dermatt, B., Goeman, J., Saerens, J., Marien, P., Pickut, B. A., Van den Broeck, M., Serneels, S., Cruts, M., Van Broeckhoven, C., and De Deyn, P. P. (2003). Prospective Belgian study of neurodegenerative and vascular dementia: APOE genotype effects. J. Neurol. Neurosurg. Psychiatry 74, 1148–1151.

Fabre, S. F., Forsell, C., Viitanen, M., Sjøgren, M., Wallin, A., Blennow, K., Blomberg, M., Andersén, C., Wahlund, L. O., and Lannfelt, L. (2001). Clinic-based cases with frontotemporal dementia show increased cerebrospinal fluid tau and high apolipoprotein E epsilon4 frequency, but no tau gene mutations. Exp. Neurol. 188, 413–418.

Farrell, A. C., van den Broeck, M., Varenberg, M., Van den Broeck, M., Varenberg, M., and Van den Broeck, M. (2008). Low plasma progranulin levels predict progranulin mutations in frontotemporal lobar degeneration. Neurology 71, 1235–1239.

Gaizauskas, B., Van Langenhove, T., van der Zee, J., Sleevers, K., Pluimets, S., Kleinberger, G., Janssens, J., Bettens, K., Van Cauwenbergh, C., Persoon, S., Engelborghs, S., Sieben, A., De Jonghe, P., Vandenberghe, R., Santens, P., De Bleeker, I., Maes, G., Baumer, V., Dillen, L., Joris, G., Cujit, I., Cornet, E., Eiink, E., Van Dongen, J., Vermeulen, S., Van den Broeck, M., Vareenberg, C., Matteijssens, M., Peeters, K., Robberecht, W., Cras, P., Martin, J. J., De Deyn, P. P., Cruts, M., and Van Broeckhoven, C. (2012). A CofD72 promoter repeat expansion in a Flanders-Belgian cohort with disorders of the frontotemporal lobar degeneration: A consensus on clinical, anatomic, and genetic features. J. Alzheimer's Dis. 314, 130–133.

Galimberti and Scarpini Genetics of FTLD

Gorno-Tempini, M. L., Hillis, A. E., Weintraub, S., Kertesz, A., Mender, M., Cappa, S. P., Ogar, J. M., Mohrer, J. D., Black, S., Boeve, B. F., Manes, F., Drönners, N. E., Van der Berghe, R., Rascovsky, K., Patterson, K., Miller, B. L., Knopman, D. S., Hodges, J. R., Masum, M. M., and Grossman, M. (2011). Classification of primary progressive aphasia and its variants. Neurology 76, 1006–1014.

Gustafson, L., Abrahamsson, M., Grubb, A., Nilsson, K., and Fax, G. (1997). Apolipoprotein-E genotyping in Alzheimer's disease and frontotemporal dementia. Dement. Geriatr. Cogn. Disord. 8, 240–243.

Gydeesen, S., Brown, J. M., Brun, A., Chakrabarti, L., Gade, A., Johannsen, P., Rossor, M., Thusaard, T., Grove, A., Yancopoulou, D., Spallanini, M. G., Fisher, E. M., Collinge, J., and Sorensen, S. A. (2002). Mutations in progranulin (granulin-epithelin precursor, PC-derived growth factor, acrogranin) mediates tissue repair and tumorigenesis. J. Mol. Med. 81, 600–612.

Helselma, S., Linnaranta, K., Lehtovirta, M., Mannernmaa, A., Heinonen, O., Rynänen, M., Riekkinen, P. R., and Soininen, H. (1996). Apolipoprotein E polymorphism in patients with different neurodegenerative disorders. Neurosci. Lett. 205, 61–64.

Holm, I. E., Englund, E., Mackenzie, I. R., Johannsen, P., and Isaacs, A. M. (2007). A reassessment of the neuropathology of frontotemporal dementia linked to chromosome 3. J. Neuropathol. Exp. Neurol. 66, 884–891.

Horser, B. A., Siddique, T., Sapp, P. C., Cargo, P. W., Dauje, J. R., Nance, M., Fan, C., Kaplan, J., Hung, W. Y., McKenna-Yasek, D., Haines, J. L., Pericak-Vance, M. A., Horvitz, H. R., and Brown, R. H. Jr. (2000). Linkage of familial amyotrophic lateral sclerosis with frontotemporal dementia: An examination of a unique disorder. Neurosci. Lett. 287, 1–4.

Hou, C. E., Carlin, D., and Miller, B. L. (2004). Non-Alzheimer's disease dementia: atypical presentations, clinical, and molecular correlates. Can. J. Psychiatry 49, 164–171.

Hutten, M., Lendon, C. L., Rizzu, P., Baker, M., Froliech, S., Houliden, M., Picking-Brown, S., Chakravarty, S., Isaacs, A., Grover, A., Hackett, J., Adamson, J., Lincoln, S., Dickson, D., Davies, P., Peteresen, R. C., Stevens, M., de Graaff, E., Wuiters, E., van Baten, J., Hillebrand, M., Jooose, M., Kwon, J. M., Nowotny, P., Che, L. K., Norton, J., Morris, J. C., Reed, L. A., Trojanowski, J., Basun, H., Lannfelt, L., Neystat, M., Fahn, S., Dark, F., Tannenberg, T., Dodd, P. R., Hayward, N., Kook, J. B., Schofield, P. R., Andreadis, A., Snowden, J., Crawford, D., Neary, D., Owen, P., Ooster, B. A., Hardy, J., Goate, A., van Swieten, J., Mann, D., Lynch, T., and Heutink, P. (1998). Association of missense and 5′-splice-site mutations in tau with the inherited dementia FTD/P17. Nature 393, 702–705.

Kimonis, V. E., Fulchiero, E., Vesa, J., and Wtts, G. (2008). VCP disease associated with myopathy, Paget disease of bone and frontotemporal dementia: review of a unique disorder. Biochim. Biophys. Acta 1782, 744–748.

Lynch, T., Sano, M., Marder, K. S., Bell, K. L., Foster, N. L., Defendini, R. F., Sima, A. A., Khoane, N., Cortes, D., de Bellerocche, X., Li, J., Jongjaroensprasert, W., Horvitz, H. R., Gunnarsson, L. G., and Brown, R. H. Jr. (2006). A locus on chromosome 9p confers susceptibility to ALS and frontotemporal dementia. Neurology 66, 839–844.

Neary, D., Snowden, J. S., Gustafson, L., Passant, U., Xuus, D., Black, B., Freedman, M., Kertesz, A., Robert, P. H., Albert, M., Boone, K., Miller, B. L., Cummings, J., and Benson, D. F. (1998). Frontotemporal lobar degeneration: a consensus on clinical diagnostic criteria. Neurology 51, 1546–1554.

Neumann, M., Sampathu, D. M., Kwong, L. K., Truax, A. C., Miszenyi, M. C., Chou, T. T., Bruce, J., Schuck, T., Grossman, M., Clark, C. M., McClusky, L. F., Miller, B. L., Masliah, E., Mackenzie, I. R., Feldman, H., Feiden, W., Kretzschmar, H. A., Trojanowski, J. Q., and Lee, V. M. (2006). Ubiquitinated TDP-43 in frontotemporal lobar degeneration and amyotrophic lateral sclerosis. Science 314, 130–133.

Parkinson, N., Ince, P. G., Smith, M. O., Highley, R., Skibinski, G., Anderssen, P. M., Morrison, K. E., Hall, H. S., Hardiman, O., Collinge, J., Shaw, P. J., Fisher, E. M., MRC Proteomics in ALS Study, and FiLeA Consortium (2006). ALS phenotypes with mutations in CHMP2B (charged multivesicular body protein 2B). Neurology 67, 1047–1047.
Venturelli, E., Villa, C., Fenoglio, C., Clerici, F., Marcone, A., Benussi, L., Ghidoni, R., Gallone, S., Cortini, F., Serpente, M., Cantoni, C., Fumagalli, G., Ridolfi, E., Cappa, S., Binetti, G., Franceschi, M., Rainero, I., Giordana, M. T., Mariani, C., Bresolin, N., Scarpini, E., and Galimberti, D. (2011). BAG1 is a protective factor for sporadic frontotemporal lobar degeneration but not for Alzheimer’s disease. *J. Alzheimers Dis.* 23, 701–707.

Venturelli, E., Villa, C., Fenoglio, C., Clerici, F., Marcone, A., Benussi, L., Ghidoni, R., Gallone, S., Scalabrini, D., Cortini, F., Fumagalli, G., Cappa, S., Binetti, G., Franceschi, M., Rainero, I., Giordana, M. T., Mariani, C., Bresolin, N., Scarpini, E., and Galimberti, D. (2010). Is KIF24 a genetic risk factor for frontotemporal lobar degeneration? *Eur. J. Neurol.* 17, 77–81.

Verpillat, P., Camuzat, A., Hannequin, D., Thomas-Anterion, C., Puel, M., Belliard, S., Dubois, B., Didic, M., Lacomblez, L., Moreaud, O., Gollier, V., Campion, D., Brice, A., and Clerget-Darpoux, F. (2002). Apolipoprotein E gene in frontotemporal dementia: an association study and meta-analysis. *Eur. J. Hum. Genet.* 10, 399–405.

Villa, C., Ghezzi, L., Pietroboni, A. M., Fenoglio, C., Cortini, F., Serpente, M., Cantoni, C., Ridolfi, E., Marcone, A., Benussi, L., Ghidoni, R., Jacini, F., Arighi, A., Fumagalli, G. G., Mandelli, A., Binetti, G., Cappa, S., Bresolin, N., Scarpini, E., and Galimberti, D. (2009). The NOS3 G894T (Glu298Asp) polymorphism is a risk factor for frontotemporal lobar degeneration. *Eur. J. Neurol.* 16, 37–42.

Venturelli, E., Villa, C., Scarpini, E., Fenoglio, C., Guidi, L., Lovati, C., Marcone, A., Cortini, F., Scalabrini, D., Clerici, F., Bresolin, N., Mariani, C., Cappa, S., and Galimberti, D. (2008). Neuronal nitric oxide synthase C276T polymorphism increases the risk for frontotemporal lobar degeneration. *Eur. J. Neurol.* 16, 870–873.

Watts, G. D., Wymer, J., Kovach, M. I., Mehta, S. G., Mumme, S., Darvish, D., Pestronk, A., Whyte, M. P., and Kimonis, V. E. (2004). Inclusion body myopathy associated with Paget disease of bone and frontotemporal dementia is caused by mutant valosin containing protein. *Nat. Genet.* 36, 377–381.

Yancopoulos, D., and Spillantini, M. G. (2003). Tau protein in familial and sporadic diseases. *Neuromolecular Med.* 4, 37–48.

Yu, C. E., Bird, T. D., Bekris, L. M., Montine, T. J., Leverenz, J. B., Steinbart, E., Galloway, N. M., Feldman, H., Woltjer, R., Miller, C. A., Wood, E. M., Grossman, M., McCluskey, L., Clark, C. M., Neumann, M., Danek, A., Galasko, D. R., Arnold, S. E., Chen-Plotkin, A., Karydas, A., Miller, B. L., Trojanowski, J. Q., Lee, V. M., Schellenberg, G. D., and Van Deerlin, V. M. (2010). The spectrum of mutations in progranulin: a collaborative study screening 545 cases of neurodegeneration. *Arch. Neurol.* 67, 161–170.

Zhu, J., Nathan, C., Jin, W., Sim, D., Ashcroft, G. S., Wahl, S. M., Lacomis, L., Erdjument-Bromage, H., Tempst, P., Wright, C. D., and Ding, A. (2002). Conversion of proopentelin to epithelins: roles of SLPI and elastase in host defense and wound repair. *Cell* 111, 867–878.

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received: 11 January 2012; paper pending published: 19 February 2012; accepted: 20 March 2012; published online: 10 April 2012.

**Citation:** Galimberti D and Scarpini E (2012) Genetics of frontotemporal lobar degeneration. *Front. Neurol.* 3:52. doi: 10.3389/neuro.2012.00052

This article was submitted to Frontiers in Dementia, a specialty of Frontiers in Neurology. Copyright © 2012 Galimberti and Scarpini. This is an open-access article distributed under the terms of the Creative Commons Attribution Non Commercial License, which permits non-commercial use, distribution, and reproduction in other forums, provided the original authors and source are credited.