Exome sequencing identifies 2 novel presenilin 1 mutations (p.L166V and p.S230R) in British early-onset Alzheimer’s disease

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A B S T R A C T

Early-onset Alzheimer’s disease (EOAD) represents 1%–2% of the Alzheimer’s disease (AD) cases, and it is generally characterized by a positive family history and a rapidly progressive symptomatology. Rare coding and fully penetrant variants in amyloid precursor protein (APP), presenilin 1 (PSEN1), and presenilin 2 (PSEN2) are the only causative mutations reported for autosomal dominant AD. Thus, in this study we used exome sequencing data to rapidly screen rare coding variability in APP, PSEN1, and PSEN2, in a British cohort composed of 47 unrelated EOAD cases and 179 elderly controls, neuropathologically proven. We report 2 novel and likely pathogenic variants in PSEN1 (p.L166V and p.S230R). A comprehensive catalog of rare pathogenic variants in the AD Mendelian genes is pivotal for a premortem diagnosis of autosomal dominant EOAD and for the differential diagnosis with other early onset dementias such as frontotemporal dementia (FTD) and Creutzfeldt-Jakob disease (CJD).

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1. Introduction

Early-onset Alzheimer’s disease (EOAD), with onset of symptoms before 65 years of age, accounts for 1%–2% of the Alzheimer’s disease (AD) cases. The disease commonly clusters within families and presents a rapid and severe progression. Generally, EOAD is a polygenic and complex disease. On the contrary, 10% of EOAD cases present a Mendelian autosomal dominant pattern of inheritance and are caused by rare and fully penetrant mutations in amyloid precursor protein (APP), presenilin 1 (PSEN1), and presenilin 2 (PSEN2), leading to Aβ42 overproduction (Coate et al., 1991; Pastor and Goate, 2004; Raux et al., 2005; Sherrington et al., 1995). PSEN1 is the most common cause of EOAD (18%–50%), with 185 mutations reported (www.molgen.database/). By contrast, APP and PSEN2 have been described in 5% and <1% of the EOAD cases, respectively (www.molgen.database/). Given the pivotal role of these genes in AD pathogenesis, a detailed catalog of pathogenic variants and an algorithm for their classification are fundamental premises for an effective genetic screening of the patients.
2. Methods

2.1. Cases and controls

Our cohort was composed of 47 independent EOAD (age at onset ≤ 65 years) autopsy proven cases and 179 elderly (> 60 years), un-related controls. Three patients reported a positive family history of AD. The other patients were referred as apparently sporadic EOAD cases.

All the patients and controls were Caucasian, mostly from the UK (London, Manchester, Nottingham, and Edinburgh) and to a lesser extent from North America. The average age at diagnosis was 57.7 years (range 41–64 years) for the EOAD patients and the mean age of ascertainment was 78 years (range 60–102 years) for the controls (Table 1).

Written informed consent was obtained for each individual and the study was approved by the appropriate institutional review boards.

2.2. Exome sequencing

Library preparation for next-generation sequencing was performed according to the NimbleGen (Roche NimbleGen v2) and TruSeq (Illumina) sample-preparation protocols. DNA libraries were then hybridized to exome-capture probes with NimbleGen SeqCap EZ Human Exome Library, version 2.0 (Roche NimbleGen) or TruSeq (Illumina). Each capture method covers the APP, PSEN1, and PSEN2 loci. Exome-enriched libraries were sequenced on the Illumina HiSeq 2000 using 2 × 100 bp paired end read cycles.

2.3. Bioinformatics

Sequence alignment and variant calling was performed against the reference human genome (UCSC hg19). Paired end sequence reads (2 × 100 bp paired end read cycles) were aligned using the Burrows-Wheeler aligner (Li and Durbin, 2009). Format conversion and indexing were performed with Picard (www.picard.sourceforge.net/index.shtml). The Genome Analysis Toolkit was used to recalibrate base quality scores, perform local re-alignments around indels, and to call and filter the variants (McKenna et al., 2010). VCFtools was used to annotate gene information for the remaining novel variants. In total, 450,987 single-nucleotide variants and 41,678 indels were called. We used snpEff v3.2 software to annotate the variants. Variants were checked against established databases (1000 Genomes Project and dbSNP v.134). The protein coding effects of variants was predicted using SIFT, PolyPhen2, and SeattleSeq Annotation (gvs.gs.washington.edu/SeattleSeqAnnotation). All variants within the coding regions of APP, PSEN1, and PSEN2 were annotated for both cases and controls.

2.4. Sanger sequencing

All rare variants identified by whole-exome sequencing in the candidate genes were validated by Sanger sequencing.

Primers for exons harboring rare variants were designed in Primer3 (http://bioinfo.ut.ee/primer3-0.4.0/) using UCSC (http://genome.ucsc.edu/) reference sequences NM_000484 (APP), NM_000213.1 (PSEN1), and NM_000447.2 (PSEN2).

Purified sequences were analyzed on an ABI 3730 DNA Analyzer (Applied Biosystems, CA, USA) and electropherograms were visualized in Sequencher software (version 4.2 Gene Codes Corporation, MI, USA).

2.5. Apoe genotyping

APOE genotypes comprising the APOE ε2, ε3, and ε4 alleles were assayed using the TaqMan method (Applied Biosystems Inc [ABI], Foster City, CA, USA). Single nucleotide polymorphism—specific primers and probes were designed by ABI (TaqMan genotyping assays).

3. Results

We report the experience of a mutation screening in APP, PSEN1, and PSEN2 in 47 EOAD unrelated cases and 179 elderly controls neuropathologically proven, from the UK. 9 EOAD cases (19%) and 5 controls (2.8%) carried at least 1 rare coding variant in the genes studied.

In our EOAD cohort, we identified a total of 8 rare coding variants in APP, PSEN1, and PSEN2, absent in controls. Of these, 3 have been previously reported in familial AD (p.C410Y and p.1131delG in PSEN1 and p.V717I in APP) (Campion et al., 1995; De Jonghe et al., 2001; Murrell et al., 2000; Tysoe et al., 1998) and 4 are novel variants: 2 detected in PSEN1 (p.L166V and p.S230R) and 2 in APP (p.K469Q and p.D620L). In addition, we report a rare and likely tolerated polymorphism in PSEN2 (p.5130L, rs63750197), present in 1 case and 1 control (Table 2).

PSEN1 p.L166V maps to the third transmembrane domain (TM3) of PS1, on the α-helix surface and corresponds to a conserved domain in PSEN2 (p.L172), where no variants or mutations have been reported. Moreover, it has been described as possibly damaging by in silico predictions (SIFT and PolyPhen2). This variant was detected in a very early onset case, presenting typical and rapidly progressing AD features with extrapyramidal signs (parkinsonism and myoclonus). At the age of 42 years, this patient developed difficulties in memory, necessitating his retirement from work. Over the next 2 years, he presented a decline in cognitive function, culminating in his medical referral. His memory loss had become more severe, he had difficulties in verbal expression, reading, writing, and calculation, and he was spatially disoriented. He had become generally apathetic. Neurologic examination revealed extrapyramidal signs and myoclonus. Neuropsychological examination revealed profound impairments in memory, language, perceptuospatial skills, and praxis. Social skills were well preserved, and he was frustrated by his difficulties.

He was reviewed at regular intervals over the following 4 years. During that time there was dramatic decline in his physical and cognitive skills. He showed marked parkinsonism and myoclonus. Speech was unintelligible, and he showed profound perceptual and spatial impairments. A single photon emission computerized tomography (SPECT) scan, 4 years after symptom onset, showed temporoparietal hypoperfusion. The profile remained typical of Alzheimer’s disease. He died aged 50 years, 8 years after onset of Alzheimer’s disease.

Table 1

| Cohort    | n   | Diagnosis                          | Sequencing strategy | Age (y) mean ± SD (range) | Male (%) | APOE ε4 (%) |
|-----------|-----|------------------------------------|---------------------|---------------------------|----------|-------------|
| EOAD      | 47  | Clinical and neuropathological     | Exome sequencing    | 57.7 (41–64)             | 55       | 57          |
| Controls  | 179 | Clinical and neuropathological     | Exome sequencing    | 78 (60–102)              | 55       | 40          |

Key: EOAD, early-onset Alzheimer’s disease; SD, standard deviation.
Table 2

| Variant | Gene Variant | Minor Allele | Controls (n = 179) | EOAD (n = 47) | Comment |
|---------|--------------|--------------|--------------------|---------------|---------|
| p.V717L | APOE ε3 | Possibly damaging | 1 (2) | 1 (2) | |
| p.L166R | APP | Possibly damaging | 1 (2) | 1 (2) | |
| p.L166R | PSEN1 | Possibly damaging | 1 (2) | 1 (2) | |
| p.L166R | PSEN2 | Possibly damaging | 1 (2) | 1 (2) | |

**Known causative mutations**
- Mutations in APP, PSEN1, and PSEN2 are the only fully penetrant variants described for EOAD. Thus, in this study we used exome-sequencing data to investigate rare coding variability in APP, PSEN1, and PSEN2, in a British cohort composed of 47 unrelated EOAD cases and 179 elderly controls. In this cohort, 6 patients of 47 (12.7%) and none of the controls carried a rare coding variant in PSEN1. This confirms that PSEN1 is the major gene involved in EOAD and suggests that rare coding variability in this gene is commonly detrimental. Among the variants detected in PSEN1, 2 are novel (p.L166V and p.S230R), likely harmful and classified as probable pathogenic, following the algorithm proposed by Guerreiro et al. (2010). These variants have been detected in 2 patients who presented the typical hallmarks of PSEN1 mutations: early onset of symptoms, aggressive symptomatology, and extrapyramidal signs (parkinsonism and myoclonus).

- PSEN1 p.L166R codon seems to be a very vulnerable site for mutations: 4 different causal mutations (p.L166del, p.L166H, p.L166P, and p.L166R) have been previously described in this same residue in 3 familial AD cases (p.L166R, p.L166H, and p.L166del) (Ezquerra et al., 2000; Knight et al., 2007; Moehlmann et al., 2002) and in 1 pseudo-sporadic case (p.L166H) (Pantieri et al. 2005). From these, p.L166R is known to be a very aggressive mutation: it causes onset of symptoms before the third decade of age, significantly increases Aβ42 production, and impairs NOTCH1 signaling in a cell culture system (Moehlmann et al., 2002). Furthermore, the amino acid...
position 166, located in the TM3 of PS1 shows a significant phylo-
genetic conservation across different species and in homologous proteins such as PS2, suggesting that the position is of functional significance.

In our cohort, the PSEN1 p.L166V variant has been detected in a patient with very young onset of age (42 years at diagnosis), thus supporting the severe effects of an amino acid substitution in this conserved residue. Surprisingly, the patient’s parents were not affected by Alzheimer’s disease. This suggests that the p.L166V may be a de novo mutation or that other genetic factors may influence the phenotype of PSEN1 mutations.

PSEN1 p.S230R clusters in the TMS domain of PS1 and is the homologous of a conserved residue in PSEN2 (p.S236). The patient carrying this variant presented a family history of AD. Recently, a different missense mutation in this codon (p.S230I) has been re-
dected in this gene (p.L166V and p.S230R). A comprehensive catalog of rare pathogenic variants in Alzheimer’s disease Mende-
lian genes is pivotal: (1) for a premortem diagnosis of EOAD pa-
tients; (2) for the differential diagnosis of other types of early onset dementias (FTD and CJD); and (3) for the identification of at risk relatives who may be potential candidates for clinical trials.

Disclosure statement

The authors have nothing to disclose.

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References

Campon, D., Flaman, J.M., Brice, A., Hannequin, D., Dubois, B., Martin, C., Moreau, V., Charbonnier, F., Didierjean, O., Tardieu, S., 1995. Mutations of the presenilin 1 gene in families with early-onset Alzheimer’s disease. Hum. Mol. Genet. 4, 2373–2377.

De Jonghe, C., Esselens, C., Kumar-Singh, S., Craessaerts, K., Sierneels, S., Checler, F., Annaert, V., Van Broeckhoven, C., De Strooper, B., 2001. Pathogenic APP mutations near the gamma-secretaase cleavage site differentially affect Abeta secretion and APPC-terminal fragment stability. Hum. Mol. Genet. 10, 1665–1671. Ezquerre, M., Carnero, C., Blesa, R., Oliva, R., 2000. A novel presenilin 1 mutation (Leu166Arg) associated with early-onset Alzheimer disease. Arch. Neurol. 57, 483–488.

Garimella, K., Altshuler, D., Gabriel, S., Daly, M., DePristo, M.A., 2010. The Genome Analysis Toolkit: a MapReduce framework for analyzing next generation DNA sequencing data. Genome Res. 20, 1297–1303. http://dx.doi.org/10.1101/gr.107524.110.

Molgen. http://www.molgen.ua.ac.be/ADMutations/.

Pantieri, R., Pardini, M., Cecconi, M., Dagna-Bricarelli, F., Vitali, A., Piccini, A., Russo, R., Borghi, R., Tabaton, M. 2005. A novel presenilin 1 I166H mutation in a pseudo-sporadic case of early-onset Alzheimer’s disease. Neurol. Sci. 26, 349–350. http://dx.doi.org/10.1007/s10072-005-0495-1.

Raux, G., Guyant-Maréchal, L., Martin, C., Bou, J., Penet, C., Brice, A., Hannequin, D., Frebourg, T., Campion, D., collaborators of GMAJ project, 2012. The French series of autosomal dominant early onset Alzheimer’s disease: an update. J. Med. Genet. 49, 793–795. http://dx.doi.org/10.1136/jmg.2011.053345.

Sherrington, R., Rogaei, E.L., Liang, Y., Rogaeva, E.A., Levesque, G., Ikeda, Y., Chi, H., Lin, C., Li, G., Holman, K., Tsuda, T., Mar, L., Foncin, J.F., Bruni, A.C., Montesi, M.P., Sorbi, S., Rainero, I., Piniessi, L., Lee, N., Chumakov, I., Pollen, D., Brooks, A., Sanseau, P., Polinsky, R.J., Wasco, W., Da Silva, H.A., Haines, J.L., Pericak-Vance, M.A., Tanz, R.E., Roses, A.D., Fraser, P.E., Rommens, J.M., St George-Hyslop, P.H. 1995. Coding of a gene bearing missense mutations in early onset familial Alzheimer’s disease. Nature 375, 754–760. http://dx.doi.org/10.1038/375754a0.

Tyssen, C., Whittaker, J., Xuereb, J., Cairns, N.J., Cruts, M., Van Broeckhoven, C., Wallin, C., Rubinsztein, D.C. 1998. A presenilin-1 truncating mutation is pre-
sent in two cases with autopsy-confirmed early-onset Alzheimer disease. Am. J. Hum. Genet. 62, 70–76. http://dx.doi.org/10.1086/301672.

Wallon, D., Rousseau, S., Ravellet-Lecuru, A., Quillard-Muraine, M., Guyant-Maréchal, L., Martinaud, O., Pariente, J., Puel, M., Rollin-Sillaire, A., Pasquier, F., Delacourte, A., Le Ber, I., Sarazin, M., Croisile, B., Boutoleau-Bretonnière, C., Thomas-Mérigoux, A., Antérion, C., Paquet, C., Moreaud, O., Gabelle, A., Sauvé, M., Lauquenière, A., Duyckaerts, C., Delisle, M.B., Stenchenberger, N., Lannes, B., Frebourg, T., Hannequin, D., Campion, D., collaborators of GMJ project, 2012. The French series of autosomal dominant early onset Alzheimer’s disease cases: mutation spectrum and cerebrospinal fluid biomarkers. J. Alzheimers Dis. 30, 847–856. http://dx.doi.org/10.3231/JAD-2012-12072.

Web references

1000 Genomes. http://www.1000genomes.org/.

dSNP. http://www.ncbi.nlm.nih.gov/projects/SNP/.

ESP. http://evs.gs.washington.edu/ESP/.

Molgen. http://www.molgen.ua.ac.be/ADMutations/.

Picard. http://picard.sourceforge.net/index.shtml.

PolyPhen 2. http://genetics.bwh.harvard.edu/pph2/.

SeattleSeq. http://snp.gs.washington.edu/SeattleSeqAnnotation138/.

SIFT. http://sift.jcvi.org/.