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## Polygenic risk score of sporadic late-onset Alzheimer's disease reveals a shared architecture with the familial and early-onset forms

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### Abstract

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#### Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jalz.2017.08.013>.

Scripts and Code: The R code and scripts we employed to perform the analysis are available in the supplementary information and also in plain text format (file PRS.r)

**Objective**—To determine whether the extent of overlap of the genetic architecture among the sporadic late-onset Alzheimer’s Disease (sLOAD), familial late-onset AD (fLOAD), sporadic early-onset AD (sEOAD), and autosomal dominant early-onset AD (eADAD).

**Methods**—Polygenic risk scores (PRSs) were constructed using previously identified 21 genome-wide significant loci for LOAD risk.

**Results**—We found that there is an overlap in the genetic architecture among sEOAD, fLOAD, and sLOAD. The highest association of the PRS and risk (odds ratio [OR] = 2.27;  $P = 1.29 \times 10^{-7}$ ) was observed in sEOAD, followed by fLOAD (OR = 1.75;  $P = 1.12 \times 10^{-7}$ ) and sLOAD (OR = 1.40;  $P = 1.21 \times 10^{-3}$ ). The PRS was associated with cerebrospinal fluid ptau<sub>181</sub>-A $\beta$ <sub>42</sub> on eADAD ( $P = 4.36 \times 10^{-2}$ ).

**Conclusion**—Our analysis confirms that the genetic factors identified for LOAD modulate risk in sLOAD and fLOAD and also sEOAD cohorts. Specifically, our results suggest that the burden of these risk variants is associated with familial clustering and earlier onset of AD. Although these variants are not associated with risk in the eADAD, they may be modulating age at onset.

### Keywords

Polygenic risk score; Sporadic late-onset Alzheimer’s disease; Early-onset Alzheimer’s disease; Early-onset autosomal dominant; Late-onset Alzheimer’s disease; Dominantly inherited Alzheimer network; *APOE*; APP; PSEN1; PSEN2; Genetic architecture; Area under the curve; Genetic risk factor; Disease modifier; Age at onset; Cerebrospinal fluid; A $\beta$ ; Tau

## 1. Introduction

Alzheimer’s disease (AD) is the most common form of dementia. In AD, the onset of cognitive impairment is preceded by a long preclinical phase, lasting approximately 15 to 20 years [1]. There is a large variability in the age at onset (AAO) of AD, and only a small fraction of cases (1%) present clinical symptoms at an early AAO (before the age of 65 years). AD has a substantial but heterogeneous genetic component. Mutations in the *amyloid  $\beta$  precursor protein* (*APP*) and *presenilin* genes [2–6] cause the Mendelian forms of AD. Although autosomal dominant AD typically is associated with early symptoms onset (autosomal dominant early-onset AD [eADAD]), some families that carry known pathogenic mutations present a late onset (onset >65–70 years) [7], suggesting a continuum between late and early onset. In addition, a large proportion of AD cases with strong familial history of dementia also present a late onset and a complex genetic architecture (familial late-onset AD [fLOAD]) [8].

Most of the sporadic AD cases present a late onset (sporadic LOAD [sLOAD]) [9] but occasionally can present an early onset (sporadic early-onset AD [sEOAD]). The apolipoprotein E (*APOE*)  $\epsilon$ 4 allele increases risk for sEOAD, sLOAD [6], and also for fLOAD [7,10] (3-fold effect size for heterozygous carriers and 12-fold for homozygous carriers [11,12]). More recent genome-wide association studies (GWASs) of LOAD have identified additional loci with moderate protective and risk effects [13–18]. The International Genomics of Alzheimer’s Project study is a case control GWAS meta-analysis includes late-onset cases from both unrelated and familial studies. Further studies suggest that polygenic

risk scores (PRSs) created based on the 21 genome-wide loci capture the overall genetic architecture of LOAD and may help to predict AD risk [10,19,20].

The PRS aggregates the effects that multiple genetic markers (both protective and risk variants) confer to individuals for a specific complex trait [21]. When employed as biomarkers, PRS can provide important insights about the prognosis of the disease and can highlight early intervention strategies as well as inclusion criteria for targeted enrollment in clinical trials. Furthermore, PRS can be employed as a measure to identify the extent of overlap between the genetic architecture of comorbid complex traits [22]. This is done by evaluating the pleiotropic effects that the markers identified in one trait have in another trait, usually evaluated in an independent cohort [20]. For example, this approach has been employed to study the shared genetic architecture between schizophrenia and cognitive function, as well as between depressive disorder and body mass index [22].

Although multiple studies have analyzed the effect of PRS in sLOAD [19,20] or fLOAD [8] cases, no study have used the PRS to compare the relative burden of risk variants in the familial versus the sporadic late-onset forms. Neither has been compared the genetic architecture of the early- versus the late-onset forms of the disease both in the familial and sporadic presentation. Therefore, a thorough evaluation of these variants will help us understand the extent of the genetic architecture shared among the different classifications of AD.

We analyzed the extent of overlap in the genetic architecture of sLOAD, fLOAD, sEOAD, and eADAD. To do so, we derived the PRS from common variants identified in the GWAS of LOAD [18] and tested it in cohorts of affected participants with European ancestry with early- and late-onset in both familial and sporadic studies. Then we tested the association of the PRS with the clinical status in each of these. Finally, we explored whether the PRS is modulating additional aspects of AD, and evaluated its association with the AAO.

## 2. Materials and methods

### 2.1. Samples

We included participants with European ancestry from the Knight-Alzheimer's Disease Research Center (Knight-ADRC) and the Dominantly Inherited Alzheimer Network (DIAN) study at Washington University [23], the Alzheimer's Disease Neuroimaging Initiative (ADNI) [24], and the National Institute on Aging Genetics Initiative for Late-Onset Alzheimer's Disease (NIA-LOAD) [25].

#### 2.1.1. Cohorts

**2.1.1.1. Autosomal dominant early-onset AD:** eADAD are defined as affected participants who carry known highly penetrant mutations in the *presenilin* or *APP* genes. All the samples were selected from the DIAN study.

**2.1.1.2. Familial LOAD:** fLOAD includes affected subjects from families with a recorded family history of AD. To be considered a fLOAD, two siblings were required to have a diagnosis of definite or probable LOAD (onset >65 years) and a third biologically-related

family member (first, second, or third degree) was also required, regardless of cognitive status. Only one proband per family was included. All the samples were selected from the NIA-LOAD study.

**2.1.1.3. Sporadic EOAD:** sEOAD were defined as participants with diagnosis of AD, with an AAO <65 years without documented familial history of AD. Samples were selected from the Knight-ADRC and ADNI.

**2.1.1.4. Sporadic LOAD:** sLOAD defined as participants with a clinical diagnosis of probable AD, AAO >65 years, and insufficient family history to qualify under the fLOAD criteria. Samples were selected from the Knight-ADRC and ADNI.

**2.1.1.5. Controls:** Controls were defined as individuals older than 65 years who after neurological assessment were determined to be nonaffected. Unrelated samples were selected from the Knight-ADRC and ADNI.

We included 236 sEOAD, 1021 sLOAD, and 687 controls from the Knight-ADRC; 122 sEOAD, 226 sLOAD, and 324 cognitively normal controls from ADNI; 1220 unrelated fLOAD from the NIA-LOAD and 249 eADAD (mutation carriers from the DIAN study).

**2.1.2. Description of the AD data sets—**Knight-ADRC research participants were evaluated by Clinical Core Personnel at Washington University. All the cases received a diagnosis of dementia of the Alzheimer's type, using criteria equivalent to the National Institute of Neurological and Communication Disorders and Stroke-Alzheimer's Disease and Related Disorders Association for probable AD [26,27] and their severity, was determined using the Clinical Dementia Rating (CDR) [28]. Controls received the same assessment as the cases but were nondemented (CDR = 0). Neuropsychological and clinical assessments and biological samples were collected for all participants as described previously [29–34]. Potential family history was obtained for all participants. Written consent was obtained from all participants. ADNI individuals were evaluated as described in the ADNI procedures manual ([www.adni-info.org](http://www.adni-info.org)).

Affected participants from the NIA-LOAD Family Study had been diagnosed with AD dementia (National Institute of Neurological and Communication Disorders and Stroke-Alzheimer's Disease and Related Disorders Association) for probable AD [27]. All individuals had a family history of AD. Probands were required to have a diagnosis of definite or probable LOAD (onset >60 years) and a sibling with definite, probable or possible LOAD with a similar AAO. A third biologically related family member (first, second, or third degree) was also required, regardless of cognitive status. If unaffected, this individual had to be  $\geq 60$  years of age, but  $\geq 50$  years of age if diagnosed with AD or mild cognitive impairment. Within each pedigree, we selected a single individual to screen by identifying the youngest affected family member with the most definitive diagnosis (i.e., individuals with autopsy confirmation were chosen over those with clinical diagnosis only).

Finally, eADAD participants (n = 249) were drawn from the DIAN [1,35]. Individuals at risk for carrying a mutation for autosomal dominant AD (i.e., *PSEN1*, *PSEN2*, or *APP*)

mutations were enrolled in the DIAN study. Participants from families with known pathogenic eADAD mutations were recruited from 197 families at six sites in the USA, one in the UK, and three in Australia [1,35]. The process of recruitment and enrollment has been described in detail previously [1,35].

## 2.2. Genotyping platforms and proxy selection

Table 1 summarizes the demographic and clinical characteristics of each clinical group. The Institutional Review Board of all participating institutions approved the study.

The fLOAD cohort is part of NIA-LOAD and was genotyped as described previously [9]. Participants, from the Knight-ADRC, DIAN, and ADNI, were genotyped with the Illumina 610 chip, Omni-express chip, or HumanCore Exome (Illumina, San Diego, CA, USA). All samples were imputed using SHAPEIT/IMPUTE2 [36,37] with the 1000 Genomes Project as reference panel [38]. We discarded genotypes that did not pass quality criteria and retained those with dosage levels  $>0.9$  across all three genotype possibilities and an information score filter  $>0.3$ .

In addition, we performed gender verification and tested for duplicates and unexpected familial relatedness, which were removed from our analysis, by estimating the pairwise genome-wide estimates of the proportion identity-by-descent. We performed standard quality control procedures on each genotyping array separately before combining data. A call rate  $\geq 98\%$  was applied for single-nucleotide polymorphisms (SNPs) and individuals. SNPs not in Hardy-Weinberg equilibrium ( $P < 1 \times 10^{-6}$ ) or with minor allele frequency (MAF)  $< 0.02$  were excluded. We inferred the population structure and confirmed the ethnicity of participants by calculating the principal components using PLINK v1.9 (<http://www.cog-genomics.org/plink2>) (Supplementary Fig. 1). Only individuals who clustered within the European-American samples were included in the study.

*APOE* genotype was determined for all individuals [33]. Briefly, *APOE*  $\epsilon 2$ ,  $\epsilon 3$ , and  $\epsilon 4$  isoforms were determined by genotyping rs7412 and rs429358 using TaqMan genotyping technology as previously described [33,39].

We employed proxy SNPs to tag the genome-wide significant loci reported for sLOAD [18] that did not pass our quality control process (Supplementary Table 1). We selected the SNPs with the highest genotyping rates, the highest  $R^2$  and  $D'$  values (in both imputed data and in the 1000 genomes) to the reported SNPs in the IGAP study [18].

## 2.3. Screening of mutation in known AD or FTD genes

We sequenced the most common genes that carry pathogenic variants for AD and frontotemporal dementia (FTD). We restricted our analysis to those genes listed in the AD&FTD Mutation Database (<http://www.molgen.vib-ua.be/ADMutations>, accessed November, 2016), particularly, we focused on *APP*, *PSEN1*, and *PSEN2* for AD and *GRN*, *MAPT*, *C9ORF72*, *CHMP2B*, *FUS*, *TARDBP*, *TBK1*, and *VCP* for FTD. The genotypes were obtained sequencing all the Mendelian genes as described elsewhere [7]. The presence of the *C9ORF72* expanded hexanucleotide repeat and the number repeats for the longest allele was determined by previously reported methods [40,41].

## 2.4. Computation of PRS

We derived a weighted PRS [21], modeling the odd ratios (ORs) as reported in IGAP study [18] (Supplementary Table 1) using a logarithm of base 2 transformation. SNPs utilized for the score would either need to have a high genotyping rate (greater than 90%) or otherwise be a reasonable proxy to the IGAP hits. We utilized PLINK v1.90b3.42 to calculate the PRS choosing the score function and the no-mean-imputation option to ensure that no scores would be imputed. The resulting mean was corrected by the multiplying allele count (log OR score).

## 2.5. Statistical analysis

The association of the PRS with case-control status was tested using a logistic regression, including age and gender as covariates. All samples within each data set were included in this analysis. Age was not included as a covariate in the eADAD analyses because the autosomal dominant AD cases were significantly younger (by design) than the controls.

The area under the curve (AUC) for receiver operating characteristic (ROC) analysis was calculated for the entire range of PRS included in each of the cohorts using the R package pROC v1.8, correcting for the same covariates as the logistic model. The areas obtained for the models were compared using the function roc.test.

To compare the effect of the PRS between the different data sets, we calculated the OR of the PRS by comparing the first versus the last tertile using logistic regression (The R Foundation for Statistical Computing v3.3.1). To analyze the eADAD cohort, we employed the functions glmer and lmer (package gee 4.13.19) clustering at family level to ascertain the effect of the PRS on clinical status and cerebrospinal fluid (CSF) biomarkers, respectively. The statistical significance between the effects of the cohorts was calculated deriving the Z-score of the absolute difference of the ORs, corrected by its standard error.

For all analyses, we employed multiple models to investigate the extent of overlap of the genetic architecture of AD under different scenarios: model 1, model 2, and model 3.

Model 1 includes the calculated PRS correcting for sex and study as well as age for the late-onset cohorts.

Model 2 extends model 1 by incorporating the effects of *APOE*  $\epsilon 2$  and  $\epsilon 4$  genotypes as covariates, which are also weighted by logarithm base 2 of the ORs (i.e.,  $\epsilon 2/\epsilon 2 = 0.6$ ;  $\epsilon 2/\epsilon 3 = 0.6$ ;  $\epsilon 2/\epsilon 4 = 2.6$ ;  $\epsilon 3/\epsilon 4 = 3.2$ ;  $\epsilon 4/\epsilon 4 = 14.9$ ) as previously reported [11]. Sex, study, and age (for the late-onset cohorts) are also included as covariates in the model 2.

In model 3, the effects of *APOE* alleles are included into the PRS, and we also corrected for sex, study, and age (for the late-onset cohorts).

Quantile regression [42] models for the relation between the PRS and the AAO for sporadic early- and late-onset participants were calculated for the 5-quantiles (quintiles) using the R package quantreg v5.29.

## 2.6. Analyte measurement

CSF tau, phosphorylated tau-181 (ptau<sub>181</sub>), and amyloid  $\beta$  42 (A $\beta$ <sub>42</sub>)—markers of neuronal injury, neurofibrillary tangles, and amyloid, respectively—were measured in the DIAN study. Biomarker values were measured following internal standards and controls [43,44]. CSF was collected in the morning under fasting conditions by means of lumbar puncture. Samples were shipped on dry ice to the DIAN biomarker core laboratory. Concentrations in the CSF of A $\beta$ <sub>1-42</sub>, total tau, and tau phosphorylated at threonine 181 were measured by immunoassay (INNOTEST amyloid  $\beta$ <sub>1-42</sub> and INNO-BIA AlzBio3; Innogenetics). All values had to meet quality-control standards, including a coefficient of variation of 25% or less, kit “controls” within the expected range as defined by the manufacturer, and measurement consistency between plates of a common sample that was included in each run. CSF values were normalized as previously described [33,45] before analyses.

## 2.7. ADNI material and methods

Data used in the preparation of this article were obtained from the ADNI database ([www.loni.ucla.edu/ADNI](http://www.loni.ucla.edu/ADNI)). The ADNI was launched in 2003 by the National Institute on Aging, the National Institute of Biomedical Imaging and Bioengineering, the Food and Drug Administration, private pharmaceutical companies, and nonprofit organizations, as a \$60 million, 5-year public-private partnership. The principal investigator of this initiative is Michael W. Weiner, M.D. ADNI is the result of efforts of many co-investigators from a broad range of academic institutions and private corporations, and subjects have been recruited from over 50 sites across the United States and Canada. The initial goal of ADNI was to recruit 800 adults, ages 55 to 90 years, to participate in the research; approximately 200 cognitively normal older individuals to be followed for 3 years, 400 people with MCI to be followed for 3 years, and 200 people with early AD to be followed for 2 years. For up-to-date information see [www.adni-info.org](http://www.adni-info.org).

## 3. Results

### 3.1. The PRS derived from genome-wide meta-analysis studies has similar effect for fLOAD and sLOAD

We initially verified the prediction accuracy of the PRS by ascertaining the cohort of sLOAD from the Knight-ADRC and ADNI participants. We observed that the PRS is significantly associated with clinical status for sLOAD (model 1: OR = 1.40;  $P = 1.21 \times 10^{-3}$ ; Table 2). Given the strong effect that *APOE* genotypes have on LOAD, we ascertained the association of the PRS correcting for the effects of *APOE* genotypes (model 2). We observed a similar OR = 1.41 ( $P = 1.33 \times 10^{-3}$ ; Table 2) that was not significantly different to the OR estimated when *APOE* was not included as a covariate ( $P_{\text{model 1 vs model 2}} = .94$ ). Then, we extended the PRS to reflect the risk and protection effects of the  $\epsilon 4$  and  $\epsilon 2$  genotypes (model 3). The addition of the *APOE* genotype increased the effect of the PRS (OR = 4.01;  $P = 5.29 \times 10^{-34}$ ; Table 2).

The ROC analysis revealed an AUC (model 3 AUC = 0.67; 95% CI = 0.65–0.69; Fig. 1), which resembles the results of other studies [10,20]. (Please refer to Supplementary Fig. 2 for the ROC curves of additional models.)

The PRS was also significantly associated with risk in the fLOAD cohort (model 1: OR = 1.75;  $P = 1.12 \times 10^{-7}$ ; Table 2). The OR of the PRS for the fLOAD did not change when we corrected for the *APOE* genotypes ( $P_{\text{model 1 vs model 2}} = .44$ ). The effect of the PRS with fLOAD was similar to that seen for sLOAD, and the strength of the association of the PRS was not statistically different ( $\text{OR}_{\text{sLOAD}} = 1.40$  vs.  $\text{OR}_{\text{fLOAD}} = 1.75$ ;  $P = .13$ ).

The model 3, which includes the effects of *APOE*  $\epsilon 2$  and  $\epsilon 4$  genotypes into the PRS, showed an OR = 7.85 ( $P = 2.52 \times 10^{-48}$ ; Table 2) for the fLOAD, which is significantly higher than the OR calculated for the sLOAD ( $\text{OR}_{\text{sLOAD}} = 4.01$  vs.  $\text{OR}_{\text{fLOAD}} = 7.85$ ;  $P = 3.01 \times 10^{-3}$ ). The AUC (model 3) for the fLOAD = 0.75 (95% CI = 0.73–0.78; Fig. 1) was also significantly higher than the AUC for sLOAD (Venkatraman's test,  $P < 2.2 \times 10^{-16}$ ). This difference is driven by a higher number of *APOE*  $\epsilon 4$  carriers in the fLOAD cohort (Table 1), as previously reported [7].

### 3.2. The effect of the PRS is significantly higher for sEOAD than for the fLOAD or sLOAD

To study possible effects that the PRS might have for sEOAD, we analyzed a cohort of participants with sEOAD included in the Knight-ADRC and ADNI studies. None of these participants carry a pathogenic mutation in the known AD or FTD genes [7,41]. We derived the PRS and included elderly nondemented participants as controls. Thus, the statistical model corrects for sex, but not age. We observed an increased OR associated with the PRS (model 1: OR = 2.27;  $P = 1.29 \times 10^{-7}$ ; Table 2), which did not differ significantly when we corrected for the effect of *APOE* genotypes ( $P_{\text{model 1 vs model 2}} = .91$ ; see Table 2). However, the OR for the sEOAD was significantly higher than the OR estimated for the fLOAD cohort ( $\text{OR}_{\text{sLOAD}} = 1.40$  vs.  $\text{OR}_{\text{sEOAD}} = 2.27$ ;  $P = 9.78 \times 10^{-3}$ ) and sLOAD ( $\text{OR}_{\text{fLOAD}} = 1.75$  vs.  $\text{OR}_{\text{sEOAD}} = 2.27$ ;  $P = 9.88 \times 10^{-3}$ ).

We also observed an increased OR when the effects of *APOE* alleles were included into the PRS (model 3: OR = 6.44;  $P = 5.80 \times 10^{-26}$ ; Table 2). The OR of the PRS with *APOE* for the sEOAD was also significantly higher than the OR calculated for the sLOAD ( $\text{OR}_{\text{sLOAD}} = 4.01$  vs.  $\text{OR}_{\text{fLOAD}} = 6.44$ ;  $P = 2.45 \times 10^{-2}$ ), but not for the fLOAD. This is driven by the high enrichment of *APOE*  $\epsilon 4$  alleles in the familial cases. Consistently with these analyses, the ROC analysis for model including the PRS and *APOE* revealed a better performance for the sEOAD AUC = 0.72 (95% CI = 0.69–0.76; Fig. 1) compared with the sLOAD (AUC = 0.67; Venkatraman's test  $P = 2.00 \times 10^{-3}$ ; Fig. 1).

To confirm that the sEOAD cases have a higher genetic burden than the sLOAD, we compared the PRS of the sEOAD versus the sLOAD directly, instead of comparing the OR. We observed that the PRS for sEOAD is significantly higher than that for sLOAD (model 1  $P = 1.95 \times 10^{-3}$  and model 2  $P = 9.04 \times 10^{-3}$ ), suggesting that these loci could explain in part the earlier onset of these cases. We observed similar results for the analysis of sEOAD cases restricted to an AAO >60 years (data not shown).

### 3.3. PRS is associated with the AAO for the AD cases with sporadic AD

The increased OR that the PRS showed for clinical status when analyzing the sEOAD compared with the one obtained for the sLOAD led us to question the possible association of PRS with the AAO. In particular, we hypothesized that the additive effects of the genome-



wide significant loci identified for LOAD would affect the AAO of AD for participants from unrelated studies, regardless of the classification of the onset of symptoms (i.e., early vs. late).

We initially verified that in our cohort of sLOAD, the PRS was associated with AAO, and as expected, a lower AAO was associated with higher PRS (model 1  $P = 1.52 \times 10^{-28}$ ; 6.3 months lower AAO per standard deviation [SD] increase of PRS; model 2  $P = 7.62 \times 10^{-3}$  and 6 months lower AAO). In contrast, the analysis within the sEOAD cohort did not show a significant association (model 1  $P = .37$  and model 2  $P = .33$ ). However, this lack of association could be due to the lower variability of the AAO in the sEOAD.

To test this hypothesis, we investigated the effect of PRS on AAO in all sporadic AD cases (including all early- and late-onset cases) in specific quantiles of the AAO. We employed quantile regression analysis to model the association of the PRS to 5-quantiles (quintiles) of AAO [46]. This analysis showed that for all the quintiles, the PRS is significantly associated with AAO ( $P < .05$ ; Supplementary Table 2 panel A). Our analyses revealed that all the coefficient estimates fall within the confidence intervals of the ordinary least squares method employed to solve linear regressions (Supplementary Fig. 3), indicating that (1) a linear regression analysis should be sufficient to analyze the association between the PRS and the entire range of AAO (lower 10.9 months per unit of SD of the PRS; model 1  $P = 1.06 \times 10^{-4}$ ) and (2) this association is not driven exclusively by the cases with older AAO, but all the cases (both early- and late-onset cases). We observed similar results when we modeled the effects of *APOE* as covariates (10.3 months lower AAO per SD increase of PRS; model 2  $P = 1.52 \times 10^{-4}$ ; see Supplementary Table 2 panel B for the quantile regression *P-values* and Supplementary Fig. 3).

These analyses indicate that the genetic factors identified for LOAD not only increase the risk for sEOAD but also their additive effects modulate the entire spectrum of AAO of sporadic AD cases.

#### 3.4. PRS is not associated with risk for eADAD but shows a significant association with CSF ptau<sub>181</sub>-Aβ<sub>42</sub> ratio

We derived the PRS, based on the genetic factors identified for LOAD, for DIAN participants. The DIAN cohort includes subjects with autosomal dominant AD, and our analyses are restricted to carriers of known pathogenic mutations in *APP*, *PSEN1*, or *PSEN2* genes. We calculated the PRS for these subjects along with elderly nondemented participants, which we employed as controls. In a similar approach to the one we employed for the sEOAD, age was not included in the model, as by design of the test, it predicts perfectly the case-control status. Our analysis did not show any significant association of the PRS with the clinical status for this cohort (model 1: OR = 0.96;  $P = 9.73 \times 10^{-1}$ ; Table 2). Neither did we observe a significant association of the PRS when we incorporated the risk conferred by the *APOE* ε4 and ε2 alleles into the PRS (model 3: OR = 0.98;  $P = 9.66 \times 10^{-1}$ ; Table 2). Nevertheless, we observed that the PRS is associated with the CSF ptau<sub>181</sub>-Aβ<sub>42</sub> ratio ( $\beta = 0.18$ ;  $P = 4.36 \times 10^{-2}$ ) and also CSF tau ( $\beta = 0.08$ ;  $P = 4.27 \times 10^{-2}$ ) in the eADAD affected participants included in the DIAN study. The CSF ptau<sub>181</sub>-Aβ<sub>42</sub> ratio was previously shown to be a strong predictor of both the progression of cognitively normal

subjects to very mild or mild dementia [47] and the rate of decline across time in individuals with very mild dementia [43]. These results suggest that if any, the effect size of the genetic architecture of LOAD is too small to be significantly identified with statistical power conferred by the cohort of eADAD; but still it also indicates that these genetic risk factors are modulating biological aspects of AD, as it is shown by the association of the PRS and the CSF ptau<sub>181</sub>-A $\beta$ <sub>42</sub> ratio.

#### 4. Discussion

To test for common genetic architecture among autosomal dominant and sporadic forms of early- and late-onset AD, we analyzed four cohorts of well-characterized participants and a common set of elderly nondemented participants. We derived PRS for the participants, assuming an additive non-interaction effect of the common (MAF > 5%) genome-wide significant variants identified for LOAD in the IGAP meta-analysis. This approach allowed us to demonstrate a significant overlap in the genetic architecture of the sporadic early-onset. In contrast, we would have required larger sample sizes if we would have used just SNPs, instead of the PRS. This is because the relatively small effect size of the genetic variants identified to LOAD. We also anticipate that the PRS will become more powerful and specific as novel GWAS loci are identified and additional variants with lower frequency (MAF < 5%) associated with AD (i.e., *TREM2* [48,49], *PLD3* [50], *SORL1* [51,52], or *ABCA7* [34,53]) are also incorporated in these analyses.

We chose to include affected participants from the NIA-LOAD, Knight-ADRC, and ADNI that were also analyzed in the IGAP study, obtaining more accurate estimates, but restricting the employment of this study as an independent replication. However, the analysis of participants from non-overlapping families with the IGAP study shown similar effects (Supplementary Table 4). Cases from families with strong incidence and cases with undetermined familial history of AD were employed in the IGAP study. In any case, our analysis showed that the fLOAD and sLOAD cases have similar burden of generic risk factors. However, the samples with a strong family history (fLOAD), independent of the pattern of heritance, show the highest percentage of *APOE*  $\epsilon$ 4 carriers, which is reflected in a higher OR once the effect of this allele is incorporated in the PRS (model 3).

Interestingly, the analysis of the sEOAD participants revealed that the PRS has a more pronounced effect on individuals with younger AAO. Indeed, this finding not only indicates that the genetic architecture is shared among sporadic cases but also suggests that AAO of AD is modulated by the additive effect of these loci. We subsequently confirmed this hypothesis identifying a similar effect for different quintiles of the AAO (Supplementary Table 2 and Supplementary Fig. 3).

We could not identify a significant association of the PRS with the eADAD cohort (DIAN). However, this cohort has the smallest number of participants. Our empirical power estimates showed that the sample size of this cohort provides a 98% chances to detect an association with ORs comparable with that observed for sEOAD. It is more likely that the lack of association of the PRS with eADAD is not because of statistical power but because the GWAS loci do not confer risk for this population, characterized by the presence of mutations

in *APP*, *PSEN1*, and *PSEN2* genes. Nonetheless, we identified an association of the PRS with the CSF ptau<sub>181</sub>-A $\beta$ <sub>42</sub> ratio in the participants with eADAD; showing that these loci have additional effects on AD pathophysiology most likely in AAO, but it could also affect disease duration or rate of progression.

Pathway analyses from the AD GWAS that includes the loci included in this study identified that the immune and inflammation as one of the most important pathways for LOAD [54]. Some of the loci included in the PRS are also clearly involved in immune response and/or inflammation (*BINI*, *CR1*, *SPI*, or *HLA* between others). This is also supported by the identification of low-frequency coding variant associated with AD risk in *TREM2*, which is clearly involved on immune response and inflammation [49,55,56]. Our results indicate that in the non-Mendelian form of the disease the immune response and inflammation play also an important role and that a higher number of risk variants in those genes will lead to an earlier onset. On the other hand, this is not the case of the Mendelian cases, in which the disease is caused by a single variant that affects A $\beta$  production [57]. However, the association of the PRS with CSF ptau<sub>181</sub>-A $\beta$ <sub>42</sub> ratio suggests that the immune response and inflammation genes also play a role in eADAD.

The effect size of the IGAP loci are lower to that of *APOE*, and the AUC for ROC indicate that the additive effect of these loci are not strong predictors of disease status (usually expected to be higher than 0.95). However, the identification of those loci are important from a biological point of view because as explained previously they identified novel pathways implicated on AD, and they are helpful to analyze potential overlap of the genetic architecture of multiple complex traits. In addition, our results indicate that individuals with familial history or earlier onset are enriched for these genetic factors. These findings can have important repercussion in the design of future genetic studies. Selecting AD cases with earlier onset (but not Mendelian mutations) or strong family history should provide more statistical power than a similar number of sporadic late-onset cases.

One limitation of this study is that to evaluate the extent of overlap of the genetic architectures among the distinct classification of AD we employed common genome-wide significant and replicated variants. A recent study indicates that the SNPs that are significant for AD risk but do not pass the stringent multiple test correction thresholds of GWASs can still be informative for the PRS [20]. Additional studies show that low-frequency variants not analyzed in GWASs are also associated with sLOAD risk [48,50]. Therefore, further studies including common and rare variants may provide more accurate estimation of the genetic burden of the sEOAD and familial samples in comparison with the sLOAD.

In conclusion, our analysis revealed an overlap among the genetic architecture of the affected participants with either strong or not familial AD history. The genetic factors identified for LOAD also affect subjects with earlier AAO who are not carriers of AD Mendelian mutation, with a higher effect in risk than that observed in the late-onset participants and modulate the age at symptom onset of AD.

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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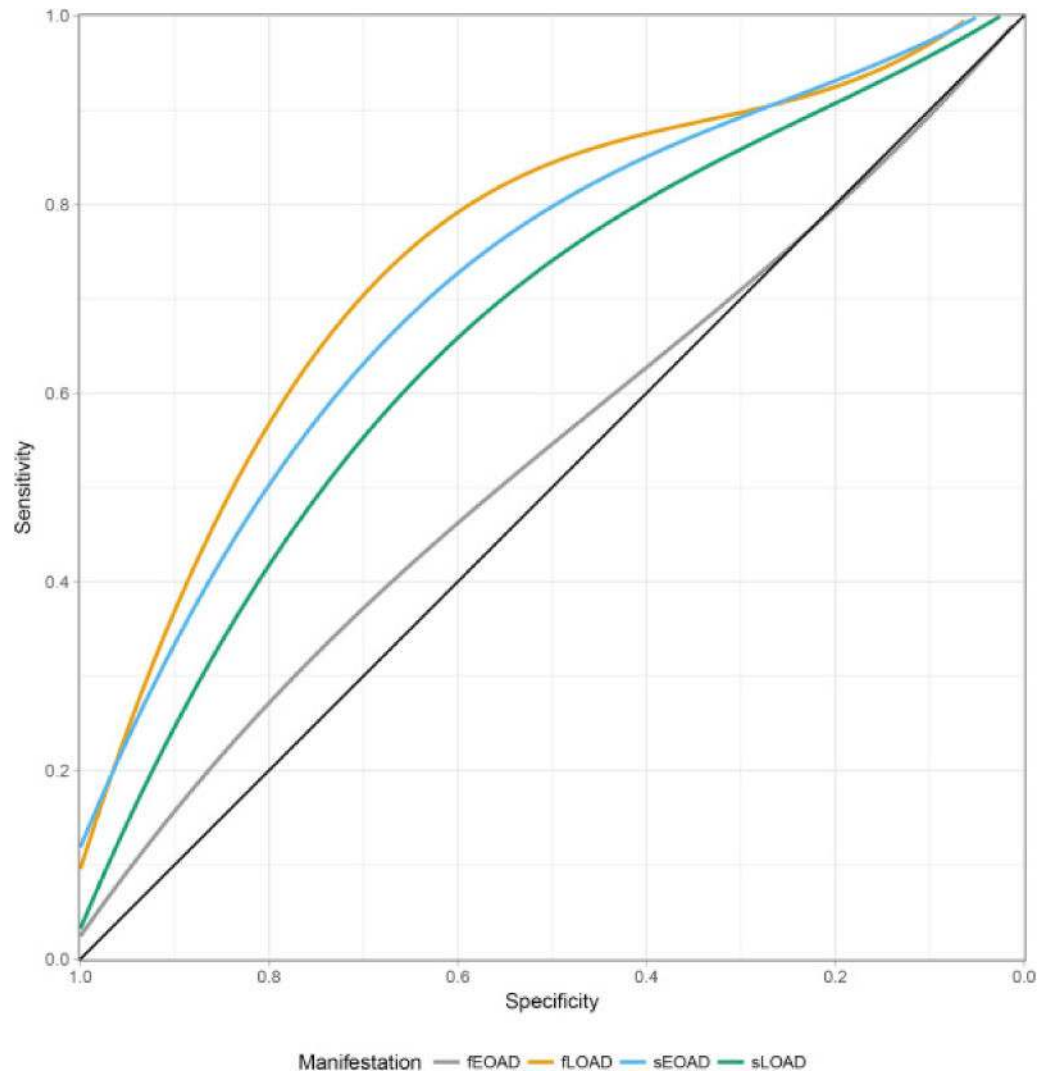
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### RESEARCH IN CONTEXT

- 1.** Systematic review: We evaluated whether the genetic architecture of sporadic late-onset Alzheimer's disease (sLOAD) is shared with sporadic early-onset (sEOAD), autosomal dominant early-onset AD (eADAD), and familial late-onset (fLOAD). Polygenic risk scores (PRSs) were constructed using 21 genome-wide significant loci identified for sLOAD.
- 2.** Interpretation: We identified an overlap in the genetic architecture among sEOAD (odds ratio [OR] = 2.27;  $P = 1.29 \times 10^{-7}$ ), fLOAD (OR = 1.75;  $P = 1.12 \times 10^{-7}$ ), and sLOAD (OR = 1.40;  $P = 1.21 \times 10^{-3}$ ), but not for the eADAD.
- 3.** Future directions: The fact that the PRS showed a higher effect size for the sEOAD and fLOAD than that observed for sLOAD can have important repercussions in the design of future genetic studies. Selecting these cases should provide more statistical power than a similar number of sLOAD. Low-frequency variants associated with AD and common variants not satisfying genome-wide threshold can improve the accuracy of the PRS and improve the understanding of the shared genetic architecture among the different manifestations of AD.





**Fig. 1.** Receiver operating characteristics—Area under the curve for the different cohorts analyzed. The lines correspond for the accuracy of obtained for the models that included gender, study, age (for late-onset data sets), and *APOE*  $\epsilon 4/\epsilon 2$  alleles. Abbreviations: fEOAD, familial early-onset Alzheimer's disease; fLOAD, familial late-onset Alzheimer's disease; sEOAD, sporadic early-onset Alzheimer's disease; sLOAD, sporadic late-onset Alzheimer's disease.

**Table 1**

## Demographics of the cohorts

Cohort	N	Female (%)	Age (SD) <sup>*</sup>	<i>APOE</i> ε4+ (%) <sup>†</sup>
Autosomal dominant early onset (DIAN)	249	57.03	37.16 (14.03)	27.18
Sporadic early onset	358	49.17	60.41 (4.83)	62.74
Familial late onset	1220	63.10	75.30 (8.34)	74.08
Sporadic late onset	1247	57.30	76.18 (7.00)	58.27
Nondemented (controls)	1011	56.38	77.03 (7.05)	31.22

Abbreviations: DIAN, Dominantly Inherited Alzheimer Network; SD, standard deviation.

<sup>\*</sup> Age at onset for affected participants and age of last assessment for non-demented subjects and for DIAN participants' age of recruitment.

<sup>†</sup> Percentage of participants' carriers of *APOE* ε4 allele.

Association results of the logistic regression models for extreme tertiles of the PRS derived for each of the cohorts and compared to nondemented participants\*

**Table 2**

Cohort	PRS (model 1)		PRS APOE corrected (model 2)		PRS with APOE effects (model 3)	
	OR	P	OR	P	OR	P
Autosomal dominant early-onset AD	0.96	$9.73 \times 10^{-1}$	0.98	$9.92 \times 10^{-1}$	0.98	$9.66 \times 10^{-1}$
Sporadic early-onset AD	2.27	$1.29 \times 10^{-7}$	2.21	$1.59 \times 10^{-6}$	6.44	$5.80 \times 10^{-26}$
Familial late-onset AD	1.75	$1.12 \times 10^{-7}$	2.01	$1.29 \times 10^{-6}$	7.85	$2.52 \times 10^{-48}$
Sporadic late-onset AD	1.40	$1.21 \times 10^{-3}$	1.41	$1.33 \times 10^{-3}$	4.01	$5.29 \times 10^{-34}$

Abbreviations: AD, Alzheimer's disease; APOE, apolipoprotein E; PRS, polygenic risk score.

\*The models correct for the sex and contributing study for the early-onset data sets and also age at onset or age of last assessment for the late-onset. The PRS was analyzed by itself (model 1). Model 2 extends it and corrects for the effects of APOE genotypes, modeling them as covariates. In the model 3, the PRS includes the risk and protection conferred by APOE genotypes. These results are a product of analyzing the tertiles with lowest and highest PRS (Please refer to Supplementary Table 3 for the analysis done in the entire range of PRS scores).