Prevalence of cerebral amyloid pathology in persons without dementia: a meta-analysis.

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Prevalence of Cerebral Amyloid Pathology in Persons Without Dementia
A Meta-analysis

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IMPORTANCE Cerebral amyloid-β aggregation is an early pathological event in Alzheimer disease (AD), starting decades before dementia onset. Estimates of the prevalence of amyloid pathology in persons without dementia are needed to understand the development of AD and to design prevention studies.

OBJECTIVE To use individual participant data meta-analysis to estimate the prevalence of amyloid pathology as measured with biomarkers in participants with normal cognition, subjective cognitive impairment (SCI), or mild cognitive impairment (MCI).

DATA SOURCES Relevant biomarker studies identified by searching studies published before April 2015 using the MEDLINE and Web of Science databases and through personal communication with investigators.

STUDY SELECTION Studies were included if they provided individual participant data for participants without dementia and used an a priori defined cutoff for amyloid positivity.

DATA EXTRACTION AND SYNTHESIS Individual records were provided for 2914 participants with normal cognition, 697 with SCI, and 3972 with MCI aged 18 to 100 years from 55 studies.

MAIN OUTCOMES AND MEASURES Prevalence of amyloid pathology on positron emission tomography or in cerebrospinal fluid according to AD risk factors (age, apolipoprotein E [APOE] genotype, sex, and education) estimated by generalized estimating equations.

RESULTS The prevalence of amyloid pathology increased from age 50 to 90 years from 10% (95% CI, 8%-13%) to 44% (95% CI, 37%-51%) among participants with normal cognition; from 12% (95% CI, 8%-18%) to 43% (95% CI, 32%-55%) among patients with SCI; and from 27% (95% CI, 23%-32%) to 71% (95% CI, 66%-76%) among patients with MCI. APOE ε4 carriers had 2 to 3 times higher prevalence estimates than noncarriers. The age at which 15% of the participants with normal cognition were amyloid positive was approximately 40 years for APOE ε4ε4 carriers, 50 years for ε2ε4 carriers, 55 years for ε3ε4 carriers, 65 years for ε3ε3 carriers, and 95 years for ε2ε3 carriers. Amyloid positivity was more common in highly educated participants but not associated with sex or biomarker modality.

CONCLUSIONS AND RELEVANCE Among persons without dementia, the prevalence of cerebral amyloid pathology as determined by positron emission tomography or cerebrospinal fluid findings was associated with age, APOE genotype, and presence of cognitive impairment. These findings suggest a 20- to 30-year interval between first development of amyloid positivity and onset of dementia.
Prevalence of Cerebral Amyloid Pathology in Persons Without Dementia

Methods

To identify relevant biomarker studies, the MEDLINE and Web of Science databases were searched for studies published before April 2015. The search terms used for PET studies were PET and (Pittsburgh or PIB or florbetapir or AV-45 or florbetaben or flutemetamol) and (amyloid or abeta). The search terms used for CSF studies were (CSF or cerebrospinal fluid) and (amyloid or abeta). Titles and abstracts were reviewed and relevant studies were retrieved. Searches were restricted to articles published in the English language. Studies were included if amyloid biomarker data for participants without dementia were reported and an a priori defined cut-off for amyloid abnormality was used. Studies that included participants with neurological, psychiatric, or other diseases that might affect the central nervous system were excluded. We also asked partners from 2 European multicenter collaborative projects, BIOMARKAPD and EMIF-AD, to provide unpublished data (Figure 1).

As most published studies did not provide prevalence estimates according to age and other risk factors, we asked study contact persons to provide participant-level data or tabulated data according to 10-year age categories and unpublished data if available. Tabulated data were converted to participant-level data with the average age in the age category. The quality of primary articles from each study was systematically assessed using relevant criteria from the STROBE guidelines and QUADAS guidelines (eTable 1 in the Supplement). All participants gave written informed consent to participate. Studies were approved by the local ethics committees of the participating centers.

Data Collection and Operationalization

Information on study procedures was extracted from the publication or requested from the study contact person and used to create a common set of variables.

Cognitive Status, APOE, Sex, and Education

Normal cognition was defined as normal scores on cognitive tests, the absence of cognitive complaints for which medical help was sought, or both. Subjective cognitive impairment was defined as presence of a cognitive complaint with presentation at a health care facility but normal cognition on tests. Mild cognitive impairment was defined according to published criteria. These include a decline in memory or another cognitive domain reported by the patient, informant, or both and objectively verified by neuropsychological testing, in combination with no or minimal impairment in activities of daily living and not meeting criteria for dementia. Mild cognitive impairment was subclassified as amnestic MCI or nonamnestic MCI when possible. Information on APOE-ε4 carrier status (yes/no), APOE genotype, and years of education was retrieved. To describe the association of APOE genotype with age, we reported for each genotype the age at which 15% of the participants with normal cognition were amyloid positive as a proxy for first appearance of abnormal amyloid.

Setting and Recruitment

The study setting was classified as clinical if patients presented with cognitive complaints at a health care facility; research if patients were asked to participate in research by recruitment through advertisements or from other hospital departments; population-based if a random sample of the general population was included; or mixed if participants were recruited from a combination of settings.

Amyloid Assessment

Measurement details documented included amyloid tracer and assessment via visual scales or quantitative measures for PET studies and assay used to measure amyloid-β1-42 levels for CSF studies. Positron emission tomography and CSF biomarkers were dichotomized as negative (normal) or positive (abnormal) according to study-specific cutoffs. (See eTables 2 and 3 in the Supplement for measurement details.) For participants who had both PET and CSF amyloid measures, we selected the first amyloid measure in time.

ALzheimer disease (AD) is the most common cause of dementia, with a worldwide prevalence of about 25 million in 2010, expected to be doubled by 2030 because of increased life expectancy. The earliest recognizable pathological event in AD is cerebral amyloid-β aggregation. This pathology may be present up to 20 years before the onset of dementia. Novel research criteria for AD in individuals without dementia emphasize the presence of amyloid pathology to define the first stage of the disease.

Prevalence estimates of amyloid pathology in persons without dementia are needed to better understand the development of AD and to facilitate the design of AD prevention studies. Initiation of treatment for AD in the predementia phase, when neuronal damage is still limited, may be crucial to have clinical benefit. Neuropathological studies have reported prevalences of amyloid pathology in nondemented individuals ranging between 10% and 60%. Studies that assessed amyloid pathology in nondemented individuals during life using biomarkers in cerebrospinal fluid (CSF) or on positron emission tomography (PET) also showed large variability in prevalence estimates (10%-70%). This variability may have resulted from small sample sizes, differences in study design, and participant selection.

The aim of this study was to estimate the prevalence of amyloid pathology as assessed by biomarkers in nondemented individuals with an individual participant meta-analysis. We estimated the prevalence in participants with normal cognition, subjective cognitive impairment (SCI), and mild cognitive impairment (MCI) and investigated the relation with known risk factors for AD-type dementia, including age, sex, education, and APOE genotype. We also tested the association of biomarker modality and recruitment strategies with prevalence estimates and compared age-specific estimates of amyloid positivity in participants with normal cognition with the prevalence of AD-type dementia in the general population.
Comparison With Prevalence of AD-Type Dementia

Age- and APOE-specific prevalence data of AD-type dementia were obtained through a meta-analysis or from published lifetime risk data for AD-type dementia as described in the eMethods in the Supplement.

Number Needed to Screen

To use the prevalence estimates in selecting participants at risk for amyloid positivity for AD prevention studies, numbers needed to screen to identify 1 amyloid-positive participant were calculated as described in the footnote of eTable 6 in the Supplement.

Statistical Analysis

We conducted a meta-analysis with individual participant data, in which original research data were sought directly from study contact persons, combined, and reanalyzed centrally. Generalized estimating equations (GEEs) were used to estimate the prevalence and odds ratios (ORs). Generalized estimating equations allow for analysis of binary correlated data such that participant-level data on the prevalence from all studies could be modeled while simultaneously accounting for the clustering of participants within studies. We assumed a logit link function for binary outcome with an exchangeable correlation structure to account for within-study correlation. Analyses were performed using SPSS version 20.0 (IBM) with the genlin command. They were conducted using the total study population unless specified otherwise.

The main analyses were performed with cognitive status (normal cognition, SCI, MCI), age, sex, education, and APOE-ε4 genotype as independent variables. Age was entered as a continuous measure centered at the median. Educational level was dichotomized at the median (high, ≥14 years, vs moderate to low, <14 years). Secondary analyses tested associations with biomarker modality, MCI subtype, published vs unpublished studies, setting, and recruitment strategy while adjusting for cognitive status, age, and APOE-ε4 carrier status. We tested 2-way and 3-way interactions between variables and age as a quadratic term, and
Prevalence of Cerebral Amyloid Pathology in Persons Without Dementia

Results

The literature search resulted in 7578 publications; amyloid was assessed by PET in 890 and by CSF in 6688. From these, 599 were selected for full-text review. We identified 47 studies from the European multicenter projects (Figure 1). A total of 91 unique studies met inclusion criteria; the authors of 55 studies agreed to share data. Contact persons from 54 studies provided participant-level data and 1 provided tabulated data (n = 137). Of the 36 studies for which contact persons refused or did not reply, 31 were selected through the literature search and 5 from the European multicenter studies. Characteristics of the 31 excluded published studies did not differ from those of the 55 included studies (eTable 4 in the Supplement).

Study Characteristics

Of the selected studies, 45 were single-center and 10 were multicenter studies. (eTable 5 in the Supplement shows detailed study information.) Forty-one studies provided data for participants with normal cognition, 20 for patients with SCI, and 47 for patients with MCI. Of the MCI studies, 8 classified patients with MCI as amnestic MCI or nonamnestic MCI, 10 studies only included patients with amnestic MCI, and all other studies used a broad MCI definition or did not specify MCI subtype. Information on APOE-ε4 carrier status was provided by 41 studies and information on APOE genotype by 37 studies. All studies but 1 specified the sex of the participants. Information on years of education was available from 44 studies. Studies contributing data for participants with normal cognition were performed in a research setting in 95% (n = 39), selection through advertisements in 15, from hospitals in 10, and from other or unknown sources in 14 and a mixed setting in 5% (n = 2). Forty-six of the studies (98%) that included patients with SCI or MCI were performed in a clinical setting.

Amyloid-PET data were provided by 29 studies. Of these, 22 studies used [11C]Pittsburgh compound-B (PiB), 9 [18F]florbetapir, 2 [18F]florbetaben, and 1 [18F]flutemetamol, including 5 that used multiple tracers. Eleven studies assessed the PET images by visual scales whereas 16 studies used quantitative assessment and 2 studies used both methods. Cerebrospinal fluid amyloid-β1-42 data were provided by 31 studies. The Innotest enzyme-linked immunosorbent assay (Fujirebio Europe) was used for CSF analysis in 29 studies and the xMAP Luminex assay in 2 studies. Two studies (1111 participants) provided data on both PET and CSF amyloid measures. Primary studies were assessed with the quality rating criteria, and typically met all criteria, although bias could not be assessed in 37 publications and participant flow remained unclear in 2 publications (eTable 1 in the Supplement).

Participant Characteristics

We included 7583 participants from 55 studies, of whom 2914 (38%) had normal cognition, 697 (9%) SCI, and 3972 (52%) MCI. Amyloid positivity was assessed with PET for 2370 participants (31%; 1346 normal cognition, 35 SCI, 989 MCI) and with CSF for 5213 participants (69%; 1568 normal cognition, 662 SCI, 2983 MCI). Baseline characteristics according to cognitive status are shown in Table 1. Participants with missing APOE data did not differ in amyloid positivity and sex from participants with APOE data but more often had limited education (63%) compared with participants who had these data available (48%; χ = 62.5, P < .001). Participants with missing sex or education data did not differ in amyloid positivity, sex, or education, and APOE-ε4 carrier status from participants with these data.

Prevalence of Amyloid Positivity

Estimated probabilities of amyloid positivity according to cognitive status, APOE-ε4 status, and age are displayed in Figure 2, Figure 3A and B, and Table 2. Observed prevalence estimates are shown in Table 3. The difference between the observed and predicted prevalence rates was less than 10% in more than 90% of the comparisons indicating good model fit. Amyloid positivity was about twice as common in patients with MCI compared with participants with normal cognition (mean difference, 25% [95% CI, 22% to 28%]; P < .001) or SCI (mean difference, 23% [95% CI, 14% to 32%]; P < .001), while it did not differ between participants with normal cognition and SCI (mean difference, 2% [95% CI, −6% to 10%]; P = .62). Amyloid positivity increased with age in all diagnostic groups.
APOE-ε4 carriers had 10% to 40% higher absolute prevalence estimates than noncarriers in each diagnostic group (Table 2, Figure 3A and B). At the median age of 70 years, the prevalence estimates were different between all APOE genotypes in participants with normal cognition, except for those of the ε2ε4 and ε3ε4 genotypes, which did not differ from each other (mean difference ε4ε4 vs ε3ε4, 38% [95% CI, 22% to 53%]; P < .001, vs ε2ε4, 28% [95% CI, 7% to 49%]; P = .008, vs ε3ε2, 60% [95% CI, 44% to 75%]; P < .001, vs ε2ε3, 73% [95% CI, 58% to 87%]; P < .001; mean difference ε3ε4 vs ε2ε4, 9% [95% CI, −1% to 20%]; P = .08, vs ε3ε2, 22% [95% CI, 18% to 26%]; P < .001, vs ε2ε3, 35% [95% CI, 29% to 40%]; P < .001; mean difference ε2ε4 vs ε3ε2, 31% [95% CI, 21% to 42%]; P < .001, vs ε2ε3, 44% [95% CI, 31% to 57%]; P < .001; mean difference ε3ε2 vs ε2ε3, 13% [95% CI, 8% to 17%]; P < .001) (Figure 3C).

After correction for multiple comparisons, ε2ε4 and ε4ε4 showed no statistically significant difference (P = .08). None of the 10 participants with ε2ε2 were amyloid positive. APOE genotype was associated with the age at onset of amyloid positivity. For example, the age at which 15% of the participants with normal cognition were amyloid positive was approximately 40 years for ε4ε4 carriers, 50 years for ε2ε4 carriers, 55 years for ε3ε4 carriers, 65 years for ε3ε3 carriers,
and 95 years for ε2ε3 carriers. In patients with SCI, prevalence of amyloid pathology according to APOE genotype was similar to participants with normal cognition in all age groups (mean difference, 1% [95% CI, −1% to 2%]; \( P = .92 \)). In patients with MCI, the prevalence differed between genotypes at the median age of 70 years, while again the ε2ε4 and ε3ε4 genotypes did not differ from each other; the difference between the ε2ε4 and ε3ε3 genotypes was not statistically significant (mean difference ε4ε4 vs ε3ε4, 23% [95% CI, 17% to 29%]; \( P < .001 \), vs ε2ε4, 33% [95% CI, 14% to 51%]; \( P = .001 \), vs ε3ε3, 54% [95% CI, 47% to 60%]; \( P < .001 \), vs ε2ε3, 64% [95% CI, 57% to 71%]; \( P < .001 \); mean difference ε3ε4 vs ε2ε4, 10% [95% CI, −9% to 28%]; \( P = .31 \), vs ε3ε3, 31% [95% CI, 25% to 37%]; \( P < .001 \), vs ε2ε3, 41% [95% CI, 34% to 48%]; \( P < .001 \); mean difference ε2ε4 vs ε3ε3, 21% [95% CI, −1% to 43%]; \( P = .06 \), vs ε2ε3, 31% [95% CI, 9% to 53%]; \( P = .005 \); mean difference ε3ε3 vs ε2ε2, 10% [95% CI, 6% to 14%]; \( P < .001 \) (Figure 3D).

Patients with MCI and the APOE ε2ε2 genotype were not included in the analysis because of the small sample size (n = 5, of whom 1 was amyloid positive). The prevalence of amyloid pathology in patients with MCI at age 70 years was 89% (95% CI, 81%–94%) for ε4ε4 carriers, 66% (95% CI, 60%–72%) for ε3ε4 carriers, 57% (95% CI, 35%–76%) for ε2ε4 carriers, 35% (95% CI, 31%–40%) for ε3ε3 carriers, and 25% (95% CI, 19%–32%) for ε2ε3 carriers. Table 4 shows the ORs for amyloid positivity of the APOE genotypes relative to the ε3ε3 genotype at age 70 years for participants with normal cognition and MCI.

The prevalence of amyloid pathology at the mean age was 5% higher (95% CI, 1% to 8%; \( P = .005 \)) in participants with an education above the median (n = 2530) than in those with education below the median (n = 2415) regardless of cognitive status, age, and APOE-ε4 carrier status (eFigure 1 in the Supplement). There was no significant association with or interaction between sex and any of the risk factors for amyloid positivity (mean difference, 1% [95% CI, −1% to 3%]; \( P = .52 \)).

**Comparison With Prevalence of AD-Type Dementia**

The age-related increase in amyloid positivity in participants with normal cognition paralleled age-specific AD-type dementia prevalence estimates, with an intervening period of about 20 years (Figure 4A). Similarly, APOE genotype–specific estimates of amyloid positivity paralleled APOE genotype–specific lifetime risks of AD-type dementia with a difference of 25 to 30 years (Figure 4B).

**Number Needed to Screen**

The numbers of participants needed to screen (NNS) to identify 1 amyloid-positive person are displayed according to age, cognitive status, and APOE genotype in eTable 6 in the Supplement. The NNS varied from 1.0 (95% CI, 1.0–1.1), for persons with normal cognition or MCI who were older than 70 years with the APOE ε4ε4 genotype, to 16.7 (95% CI, 11.1–25.0), for persons with normal cognition aged 50 years without an APOE-ε4 allele. If APOE genotype is unknown, participants need to be screened for this first. The number of participants for whom APOE genotyping needs to be performed to find 1 participant with that particular APOE genotype who is amyloid positive varied between 3.5 (95% CI, 2.8–4.3), for persons with normal cognition aged 90 years without an APOE-ε4 allele, to 89.6 (95% CI, 64.5–129.0), for persons with normal cognition aged 50 years with the APOE ε4ε4 genotype.

**Assessment of Study-Related Heterogeneity**

In the total study population, the intraclass correlation coefficient for study-related random intercept variance was 0.085, indicating minor heterogeneity among studies. Within age, APOE-ε4, and diagnostic subgroups, heterogeneity was not substantial according to the \( F \) statistic, except for 2 of 54 subgroups (50%–60% in age group 65–69 years of SCI, APOE-ε4 carriers and in age group 75–79 years of MCI APOE-ε4 noncarriers) (eTable 7 in the Supplement). Visual inspection of variability in prevalence estimates across age in studies with at least 50 participants also indicated that between-study variability was small (eFigure 2 in the Supplement).

**Post Hoc Analyses**

The biomarker used to assess amyloid positivity was not associated with prevalence (mean difference, 0% [95% CI, −7% to 8%]; \( P = .87 \)) for participants with normal cognition or MCI (n = 6885). Patients with SCI were excluded because amyloid was measured with PET in only 5% of participants. While adjusting for APOE-ε4 carrier status and age, amyloid prevalence at the mean age was higher in patients with amnestic MCI (n = 1405) than in patients with nonamnestic MCI (n = 225, 58% [95% CI, 48% to 67%] vs 47% [95% CI, 35% to 60%], mean difference, 11% [95% CI, 0% to 21%]; \( P = .03 \)) and higher in patients with nonamnestic MCI than in participants with normal cognition (n = 2289, mean difference, 15% [95% CI, 2% to 28%]; \( P = .03 \)). The prevalence...
did not differ between amnestic MCI (n = 1405) and MCI patients diagnosed using a broad or unspecified definition of MCI (n = 1487, mean difference, 3% [95% CI, −6% to 13%]; \( P = .51 \)). Prevalence estimates did not differ for published and unpublished studies (eTable 8 in the Supplement). The prevalence in participants with normal cognition recruited via advertisements (n = 1868) was similar to that of participants recruited from hospital departments (n = 305, mean difference, 4% [95% CI, −13% to 21%]; \( P = .96 \)).

**Discussion**

This amyloid biomarker study including individuals without dementia provides prevalence estimates of amyloid pathology over an age range of 18 to 100 years for persons with normal cognition, SCI, and MCI. The age at onset of amyloid positivity was associated with cognitive status and the **APOE** genotype. At age 90 years, about 40% of the **APOE-ε4** noncarriers and more than 80% of **APOE-ε4** carriers with normal cognition were amyloid positive. Amyloid positivity was associated with education but not with sex or biomarker modality. The age-related prevalence of amyloid positivity in participants with normal cognition paralleled the age-related prevalence of AD-type dementia in the general population in an **APOE** genotype–specific way with a time lag of 20 to 30 years.

Patients with MCI had 20% to 30% higher prevalence estimates of amyloid positivity than those with normal cognition or SCI, supporting the view that MCI is a risk state for AD.\(^{16}\) Cognitively normal and SCI groups did not differ in amyloid positivity, suggesting that the presence of SCI in a memory clinic population might not be associated with an increased risk for AD. Previous studies in other settings showed inconsistent results regarding differences in amyloid positivity between cognitively normal and SCI participants.\(^{20,21}\) indicat-
ing that further research is needed on this. Patients with nonamnestic MCI had lower prevalence estimates of amyloid positivity than patients with amnestic MCI but higher than participants with normal cognition. This suggests that both amnestic MCI and nonamnestic MCI are associated with an increased risk for AD and that this risk is higher for patients with amnestic MCI. The observation that a substantial number of patients with MCI were not amyloid positive, even at older age, suggests that the MCI phenotype does not always have AD as underlying pathology. Possible non-AD causes in MCI may be hippocampal sclerosis, mild depression, or vascular damage.

**Table 2. Prevalence Estimates of Amyloid Positivity According to Age, Cognitive Status, and APOE-ε4 Carrier Status**

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**Table 3. Observed Probabilities of Amyloid Positivity**

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<td>51.4</td>
<td>54.5</td>
</tr>
<tr>
<td>72.5-77.4 y</td>
<td>32.2</td>
<td>61.3</td>
<td>57.2</td>
</tr>
<tr>
<td>77.5-82.4 y</td>
<td>42.0</td>
<td>65.5</td>
<td>63.1</td>
</tr>
<tr>
<td>82.5-87.4 y</td>
<td>49.0</td>
<td>76.5</td>
<td>60.3</td>
</tr>
<tr>
<td>87.5-92.4 y</td>
<td>51.0</td>
<td>87.5</td>
<td>61.4</td>
</tr>
</tbody>
</table>

**Abbreviations:** APOE, apolipoprotein E; MCI, mild cognitive impairment; SCI, subjective cognitive impairment.

* The prevalence estimates were generated from generalized estimating equations. Amyloid positivity in the total group was modeled using age and cognitive status as predictors. Amyloid positivity according to APOE-ε4 status was modeled with age, cognitive status, APOE-ε4 status, an interaction between age and cognitive status, and an interaction between age and APOE-ε4 status. Table 3 displays the number of participants and observed probabilities of amyloid positivity per age subgroup. No estimate was provided if the 5-year range around the indicated column age included no participants.

* No participants available with the exact age; prevalence estimated at nearest age.
creased age at onset, while the APOE-ε2 allele had the opposite associations. This is similar to the relation of APOE genotype with the risk for AD-type dementia and age at onset of AD-type dementia as reported in clinical studies\(^{25,26}\) and the APOE genotype-specific lifetime risk for AD as shown in Figure 4B. The high prevalence of amyloid positivity in participants with normal cognition and MCI with ε2ε4 in the present study indicates that the detrimental relation of amyloid positivity with ε4 outweighs the protective association with ε2, in line with clinical AD studies.\(^{27}\) The OR for amyloid pathology of the APOE genotypes relative to the ε3ε3 genotype was similar to the OR for AD-type dementia in case-control studies.\(^{18,27}\) The strong association of the APOE genotype with amyloid positivity emphasizes APOE as an important target for treatment studies.\(^{28,29}\)

Highly educated participants had a higher prevalence of amyloid pathology than those with less formal education. This may seem in contrast with the finding that high education level is associated with a lower risk for AD-type dementia\(^{20}\) but is in agreement with the cognitive reserve hypothesis.\(^{31}\) According to this hypothesis, nondemented individuals with a high level of education have a greater cognitive reserve such that they can sustain more amyloid pathology before developing dementia. Education itself was not associated with the ex-

---

**Table 4. Odds Ratios for the Association Between APOE Genotype and Amyloid Positivity at Age 70 Years**

<table>
<thead>
<tr>
<th>APOE Genotype</th>
<th>Normal cognition</th>
<th>MCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>ε3ε3</td>
<td>1 (Reference)</td>
<td>1 (Reference)</td>
</tr>
<tr>
<td>ε2ε3</td>
<td>0.34 (0.23-0.51)</td>
<td>0.59 (0.48-0.73)</td>
</tr>
<tr>
<td>ε2ε4</td>
<td>4.29 (2.67-6.90)</td>
<td>2.38 (0.98-5.81)</td>
</tr>
<tr>
<td>ε3ε4</td>
<td>2.94 (2.34-3.70)</td>
<td>3.52 (2.73-4.55)</td>
</tr>
<tr>
<td>ε4ε4</td>
<td>18.76 (5.47-64.37)</td>
<td>14.50 (8.14-25.81)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No. amyloid positive (%)</th>
<th>Normal cognition</th>
<th>MCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>ε3ε3</td>
<td>275 (22.4)</td>
<td>490 (38.7)</td>
</tr>
<tr>
<td>ε2ε3</td>
<td>22 (8.6)</td>
<td>57 (27.0)</td>
</tr>
<tr>
<td>ε2ε4</td>
<td>22 (8.6)</td>
<td>17 (41.5)</td>
</tr>
<tr>
<td>ε3ε4</td>
<td>17 (41.5)</td>
<td>56 (33.9)</td>
</tr>
<tr>
<td>ε4ε4</td>
<td>8 (2.2)</td>
<td>12 (2.2)</td>
</tr>
</tbody>
</table>

Abbreviations: APOE, apolipoprotein E; OR, odds ratio; MCI, mild cognitive impairment.

a The ORs were generated from generalized estimating equations separately in participants with normal cognition and MCI. The models included age, APOE genotype, an interaction between age and APOE genotype, and a quadratic age term in the normal cognition model as predictors. P values represent the significance of the OR for amyloid positivity compared with the ε3ε3 genotype. The ε2ε2 genotype was excluded because of the small number of participants in this group.

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**Figure 4. Comparison of the Prevalence of Amyloid Positivity With the Prevalence of and Lifetime Risks for Alzheimer Disease-Type Dementia**

A. Prevalence of Alzheimer disease and amyloid positivity

B. Lifetime risk of Alzheimer disease and amyloid positivity by APOE genotype

The prevalence estimates in panel A were estimated from a meta-analysis of 14 studies (eMethods in the Supplement). The prevalence estimates in panel B of amyloid positivity in participants with normal cognition are plotted against published lifetime risks for Alzheimer disease (AD)-type dementia by APOE genotype (adapted from Genin et al\(^{18}\)).
tent of pathology at postmortem examination has not yet been validated.

The prevalence of amyloid positivity was higher among men than women, and this finding was also in agreement with another earlier study. Our findings support the hypothesis that amyloid positivity in these individuals reflects early AD. Further support for this hypothesis comes from studies that show that amyloid positivity in nondemented individuals is associated with memory impairment, cognitive decline, increased amyloid deposition, and brain atrophy rates, and mortality. Our study also indicates that development of AD pathology can start as early as age 30 years, depending on the APOE genotype. Comparison with prevalence and lifetime risk estimates of AD-type dementia suggests a 20- to 30-year interval between amyloid positivity and dementia, implying that there is a large window of opportunity to start preventive treatments. Still, the exact interval between the onset of amyloid positivity and onset of AD-type dementia needs to be assessed by long-term follow-up studies because not all persons with amyloid pathology will become demented during their lifetime, and not all individuals with a clinical diagnosis of AD-type dementia have amyloid pathology. Because of the uncertainty about whether and when an amyloid-positive individual without dementia will develop dementia, amyloid positivity in these individuals should not be equated with impending clinical dementia but rather be seen as a risk state. Our prevalence rates can be used as an inexpensive and noninvasive approach to select persons at risk for amyloid positivity.

Conclusions

Among persons without dementia, the prevalence of cerebral amyloid pathology as determined by PET imaging or CSF findings was associated with age, APOE genotype, and presence of cognitive impairment. These findings suggest a 20- to 30-year interval between first development of amyloid positivity and onset of dementia.
Prevalence of Cerebral Amyloid Pathology in Persons Without Dementia

Original Investigation  
Research

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Author Contributions: Ms Jansen and Dr Visser had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis.

Study concept and design: Jansen, Ossenkoppele, Verhey, Visser.

Acquisition, analysis, or interpretation of data: All authors.

Drafting of the manuscript: Jansen, Visser.

Critical revision of the manuscript for important intellectual content: All authors.

Statistical analysis: Jansen, Knol, Visser.

Administrative, technical, or material support: All authors.

Study supervision: Visser.

Conflict of Interest Disclosures: All authors have completed and submitted the ICMJE Form for Disclosure of Potential Conflicts of Interest. Dr Scheltens reported receiving grants from GE Healthcare, Piramal, and Merck, paid to his institution. Dr Verhey reported receiving compensation as a speaker and consultant for Nutricia Advanced Medical Food. Dr Visser reported receiving grants from EUnetPIA Innovative Medicines Initiative Joint Undertaking, EU Joint Programme-Neurodegenerative Disease Research (JPN), ZonMW, and Bristol-Myers Squibb, having served as member of the advisory board of Roche Diagnostics, and having received nonfinancial support from GE Healthcare. Dr Aarsland reported having received research support or honoraria from Astra-Zeneca, H. Lundbeck, Novartis Pharmaceuticals, and GE Health. Dr Alexander reported being an employee of Roche Products. Dr Barthel reported receiving a speaker and consultant honoraria as well as travel expenses from Piramal Imaging (Berlin) and personal fees from Siemens Healthcare. Dr Bibeau reported being a share-holding employee of GlaxoSmithKline. Dr Blennow reported receiving personal fees (advisory board) from Roche Diagnostics, IBL International, Novartis, and Eli Lilly. Dr Brooks reported having served as consultant for GE Healthcare. Dr Camus reported having received grants from the National Institutes of Health (NIH). Dr Dzeguze reported having received speaker honoraria and consulting fees from GE Healthcare, Avid/Lilly, and Piramal. Dr Fagan reported having received grants from NIH, Fred Simmons and Olga Mohan, and Charles and Joanne Knight Alzheimer’s Research Initiative of the Washington University Knight Alzheimer’s Disease Research Center, and having received personal fees from NIH, Fred Simmons and Olga Mohan, and Charles and Joanne Knight Alzheimer’s Research Initiative of the Washington University Knight Alzheimer’s Disease Research Center; having received personal fees from IBL, International, Roche, and AbbVie; and having a patent, 6,465,195 B2, “Predictive diagnostic for Alzheimer’s disease,” issued and a patent, PCT/US2015/062233, “A risk factor and new therapeutic target for Alzheimer’s disease,” pending. Dr Fladby reported having a patent “Methods and systems for monitoring phagocytic activity,” PCT/US2015/062233, pending. Dr Fleisher reported having been a full-time employee of the Banner Alzheimer’s Institute; being a full-time employee of Eli Lilly; maintaining a voluntary faculty appointment at the University of California, San Diego; having been a member of data and safety monitoring boards for Merck, Pfizer, and the National Institute of Aging (NIA); having received grant funding from NIA and Avid Radiopharmaceuticals and having been a consultant for Eli Lilly, Grifols, Avid Radiopharmaceuticals, and Siemens Imaging. Dr van der Flier reported having received grants from Boehringer Ingelheim, Piirama Imaging, and Roche. Dr Förster reported having received personal fees (consultancy) from Piramal, Bayer, and GE. Dr Foskett reported being a full-time employee of Roche Prod and holding Roche shares and share options. Dr Frisoni reported having received grants and/or personal fees from Lilly, Bristol-Myers Squibb, Bayer, Liva, Roche, Piramal, and the Alzheimer’s Association. Dr Gill reported having received grants from the Indian Council of Medical Research, New Delhi, India. Dr Gordon reported being a salaried employee of Boehringer Ingelheim Pharma GmbH, Liva, Novartis, Eisai, Pfizer, sanofi-aventis, Roche Pharmaceuticals and Diagnostics, UCB, Novartis, Avi, Eli Lilly, GlaxoSmithKline Biologicals, Jung-Diagnostics, and Cytox and having a patent, “Method for predicting whether subjects with mild cognitive impairment (MCI) will develop Alzheimer’s disease,” pending; a patent, “3-Hydroxykynurenin um Serun als diagnosticscher Marker für die Demenz vom Alzheimer-Typ,” pending; a patent, “Neurodegenerative markers for psychiatric conditions,” pending; a patent, “Ratio A9/42/40 in the Plasma in der Früh- und Differenzialdiagnose der Alzheimers Krankheit,” pending; a patent “Liquordiagnostisches in vitro Verfahren zur Diagnose von Demenz Erkrankungen und neuroinflammatorischen Erkrankungen,” pending; and a patent, “In vitro Verfahren zur Diagnose von neurodegenerativen Erkrankungen,” pending. Dr Hellwig reported having received grants from GE Healthcare and Medical Faculty, University of Freiburg. Dr Ichihara reported being an employee and shareholder of GlaxoSmithKline. Dr Jagust reported having received personal fees from Banner Alzheimer Institute/Genetech, Synarc/Bioclinica, and Novartis. Dr Kandimalla reported having received grants from the Indian Council of Medical Research, India. Dr Kapaki reported having received grants from the European Union (European Regional Development Fund [ERDF]) and Greek national funds through the Operational Program “Competitiveness and Entrepreneurship” of the National Strategic Reference Framework (NSRF) Research Funding Program: Joint Programming Neurodegenerative Disease, “Biomarkers for Alzheimer’s disease and Parkinson’s disease.” Dr Klunk reported being a co-inventor of the amyloid imaging tracer PiB and, as such, having a financial interest in the license agreement. (PiB intellectual property is owned by the University of Pittsburgh, and GE Healthcare has a license agreement with the University of Pittsburgh based on the PiB technology described in this article. Dr Klunk receives “inventor share” payments from the University of Pittsburgh based on income from that license.) Dr Koglin reported having received personal fees from employment at Piramol Imaging, who is marketing Neuraceq.

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Prevalence of Cerebral Amyloid Pathology in Persons Without Dementia

Original Investigation Research


Correction:

Acknowledgement_List.pdf. Additional investigators can be found at http://adni.loni.usc.edu. Investigators provided data but did not participate in analysis or design and implementation of ADNI and/or contributed to the database (http://adni.loni.usc.edu). As such, the investigators with the ADNI contributed to the data collection and implementation of ADNI and/or provided data but did not participate in analysis or writing of this report. A complete listing of ADNI investigators can be found at http://adni.loni.usc.edu/wp-content/uploads/how_to_apply/ADNI_Acknowledgement_List.pdf. Additional information is available in the Supplement.

Correction: This article was corrected online May 19, 2015, to fix curves in Figure 3C.

REFERENCES


