Association of β-Amyloid Level, Clinical Progression, and Longitudinal Cognitive Change in Normal Older Individuals

Laura M. van der Kall, MSc, Thanh Truong, BH-BMed, Samantha C. Burnham, PhD, Vincent Doré, PhD, Rachel S. Mulligan, PhD, Svetlana Bozinovski, RN, Fiona Lamb, DPsych, Pierrick Bourgeat, PhD, Jurgen Fripp, PhD, Stephanie Schultz, MSc, Yen Y. Lim, PhD, Simon M. Laws, PhD, David Ames, MD, Christopher Fowler, PhD, Stephanie R. Rainey-Smith, PhD, Ralph N. Martins, PhD, Olivier Salvado, PhD, Joanne Robertson, DPsych, Paul Maruff, PhD, Colin L. Masters, MD, Victor L. Villemagne, MD, and Christopher C. Rowe, MD

Neurology® 2021;96:e662-e670. doi:10.1212/WNL.0000000000011222

Correspondence
Dr. Rowe
christopher.rowe@austin.org.au

Abstract

Objective
To determine the effect of β-amyloid (Aβ) level on progression risk to mild cognitive impairment (MCI) or dementia and longitudinal cognitive change in cognitively normal (CN) older individuals.

Methods
All CN from the Australian Imaging Biomarkers and Lifestyle study with Aβ PET and ≥3 years follow-up were included (n = 534; age 72 ± 6 years; 27% Aβ positive; follow-up 5.3 ± 1.7 years). Aβ level was divided using the standardized 0–100 Centiloid scale: <15 CL negative, 15–25 CL uncertain, 26–50 CL moderate, 51–100 CL high, >100 CL very high, noting >25 CL approximates a positive scan. Cox proportional hazards analysis and linear mixed effect models were used to assess risk of progression and cognitive decline.

Results
Aβ levels in 63% were negative, 10% uncertain, 10% moderate, 14% high, and 3% very high. Fifty-seven (11%) progressed to MCI or dementia. Compared to negative Aβ, the hazard ratio for progression for moderate Aβ was 3.2 (95% confidence interval [CI] 1.3–7.6; p < 0.05), for high was 7.0 (95% CI 3.7–13.3; p < 0.001), and for very high was 11.4 (95% CI 5.1–25.8; p < 0.001). Decline in cognitive composite score was minimal in the moderate group (−0.02 SD/year, p = 0.05), while the high and very high declined substantially (high −0.08 SD/year, p < 0.001; very high −0.35 SD/year, p < 0.001).

Conclusion
The risk of MCI or dementia over 5 years in older CN is related to Aβ level on PET, 5% if negative vs 25% if positive but ranging from 12% if 26–50 CL to 28% if 51–100 CL and 50% if >100 CL. This information may be useful for dementia risk counseling and aid design of preclinical AD trials.
β-amyloid (Aβ) deposition begins decades prior to dementia due to Alzheimer disease (AD) and is an important predictor of mild cognitive impairment (MCI) or dementia in cognitively normal (CN) individuals. Preventative treatments should target this early stage of the disease and identifying those at highest risk of decline would allow faster clinical trials.

In most current clinical practice and research settings, Aβ PET scans are classified as positive or negative, but limited data suggest that the risk of progression is related to the level of Aβ in individuals with a positive scan.

The Centiloid (CL) scale was developed to standardize Aβ imaging measures and to aid the adoption of widely applicable thresholds for PET Aβ levels that correspond with histopathologic classification and correlate with prognosis. Zero CL corresponds to the mean scan measure of healthy young adults without Aβ deposition and 100 CL corresponds to the mean scan measure of patients with mild AD dementia. Twenty-five CL corresponds approximately with the discrimination between a positive vs a negative scan by an expert visual reader, and with most standardized uptake value ratio (SUVR) thresholds.

The objective of this study was to determine the effect of Aβ level expressed in CL on the progression risk to MCI or dementia in CN individuals. We further examined associations between Aβ burden and longitudinal change in cognition.

Methods

Participants
A total of 534 CN individuals from the Australian Imaging, Biomarkers and Lifestyle (AIBL) study with at least 3 years of clinical follow-up after an Aβ PET scan were identified. They underwent a screening visit consisting of a clinical and neuropsychological assessment, APOE genotyping, and Aβ PET and MRI scans. Participants were followed longitudinally at approximately 18-month intervals. After each visit, a clinical panel reviewed the neuropsychological information of the participants blinded to all imaging findings and the participants were classified as CN or were diagnosed with MCI, AD, or other dementia. Diagnosis was based on standard clinical criteria for MCI and AD. Participants diagnosed with MCI or any type of dementia during the follow-up period were classified as progressors and participants not meeting any criteria for MCI or dementia were classified as clinically stable.

Genotyping of APOE was determined by direct sequencing at baseline. Participants with at least 1 APOE ε4 allele were classified as APOE ε4 carriers.

Standard Protocol Approvals, Registrations, and Patient Consents
Written informed consent was obtained from all participants. Data from the AIBL study was used and a detailed description of the AIBL methods can be found elsewhere. The AIBL study was approved by the ethics committee of St Vincent’s Health, Austin Health, Hollywood Private Hospital, and Edith Cowan University.

Neuropsychological Evaluation
All participants received the AIBL neuropsychological test battery as previously described in detail.

To assess cognitive performance longitudinally, 3 measures were used: Clinical Dementia Rating Sum of Boxes (CDR-SOB), California Verbal Learning Test II long delay free recall (CVLT-II LDFR), and a cognitive composite score called the AIBL–Preclinical AD Cognitive Composite (PACC). The AIBL-PACC is based on the ADCS-PACC derived by Donohue et al. and has been shown to be sensitive for deterioration in cognition in clinically normal older cohorts. The AIBL-PACC consists of the Mini-Mental State Examination, Digit Symbol Substitution Test from the Wechsler Adult Intelligence Scale, CVLT-II LDFR, and Logical Memory Ia subtest from the Wechsler Memory Scale. For each individual, the Z scores of each of the 4 test scores were mean averaged to give a PACC Z score.

Imaging Methods and Analysis
Aβ PET imaging was conducted using Aβ tracers: 11C–Pittsburgh compound B (PiB), 18F-florbetapir, or 18F-flutemetamol. As described previously, PET acquisitions were performed 40–70 minutes post-tracer injection (PI) for 11C-PiB, 50–70 minutes PI for 18F-florbetapir, and 90–110 minutes PI for 18F-flutemetamol. PET images were not corrected for partial volume correction. All Aβ PET scans were quantified using CapAIBL and the Aβ level was expressed in CLs as described by Klunk et al. and Bourgeat et al. Aβ level was classified according to 5 categories: <15 CL negative, 15–25 CL uncertain, 25–50 CL moderate, 51–100 CL high, >100 CL very high. The category limits were chosen prior to data analysis based on published CL information. Notably, studies reporting CL findings in younger controls aged under 45 years give an average of 11 CL as the 2 SD upper limit above the mean of 0 CL, while postmortem correlation studies indicate

Glossary

Aβ = β-amyloid; AD = Alzheimer disease; ADNI = Alzheimer’s Disease Neuroimaging Initiative; AIBL = Australian Imaging, Biomarkers and Lifestyle; CDR-SOB = Clinical Dementia Rating Sum of Boxes; CL = Centiloid; CN = cognitively normal; CVLT-II LDFR = California Verbal Learning Test II long delay free recall; HA = hippocampal atrophy; HR = hazard ratio; HV = hippocampal volume; MCI = mild cognitive impairment; PACC = Preclinical AD Cognitive Composite; PI = post-tracer injection; PiB = Pittsburgh compound B; SUVR = standardized uptake value ratio.
Consortium to Establish a Registry for Alzheimer’s Disease (CERAD)–classified moderate neuritic plaque density may be found at 15 CL but usually is associated with >25 CL.12–18 Consequently, we set <15 CL as negative, 15–25 as uncertain, and then, to reflect categories that may be useful to a clinician for determining individual prognosis, divided the traditionally positive scans into the 3 categories of moderate, high, and very high.

3T MRI 3D magnetization-prepared rapid gradient echo was used to measure hippocampal volume (HV) corrected for whole brain volume.26 Using the HV of the AIBL CN and AD groups, the Youden Index was applied to determine optimal HV cutoff value for hippocampal atrophy (HA), yielding HA ≤ 2.74 cm³ for sensitivity 85%, specificity 86%.

### Statistical Analyses
Statistical analyses were performed using RStudio, version 3.5.3, with statistical significance at p < 0.05. Differences between the progressors and the clinically stable group were assessed with independent t test for continuous data (age, years of education, and length of follow-up), χ² testing for categorical data (sex, APOE ε4 status, and HA), and Fisher exact test (Aβ categories).

Cox proportional hazards analysis was used to examine the effect of the Aβ levels and other measures (age, sex, years of education, APOE ε4 status, low baseline memory performance, and HA) on clinical progression to MCI or dementia. The visit with the first PET scan was identified as the baseline visit and the event was classified as the progression to MCI or dementia. Survival was defined as the time between baseline and the event, or withdrawal, or the last available follow-up examination. We also analyzed the data truncated at the 4.5-year follow-up due to concern about the relatively small number of at risk Aβ-positive individuals beyond this point.

For this analysis, age and years of education were dichotomized by using a cutoff value of 72 years for age and ≤13 years for education (mean of this CN cohort). CVLT-II LDFR was used to classify CN participants as low memory performance at baseline when the Z score was ≤−1.0 using the mean and SD of the CN cohort with no correction for age but they did not meet criteria for MCI. Hazard ratios (HRs) were calculated to examine the effect of the factors on progression.

Linear mixed effects models were performed to examine the association between Aβ level and the longitudinal change in cognitive performance. Three models were created for the following variables: AIBL-PACC, CVLT-II LDFR, CDR-SoB. Time from baseline (years), Aβ level, and their interaction were included as fixed effects. Participant identification

### Table 1 Participant Characteristics

|                                | All (n = 534) | Progressors (n = 57) | Clinically stable (n = 477) |
|--------------------------------|---------------|----------------------|-----------------------------|
| Age, y                         | 72 ± 6 (56–90) | 74 ± 6 (62–88)       | 72 ± 6 (56–90)†             |
| Female                         | 295 (55)      | 27 (47)              | 268 (56)                    |
| Education, y                   | 13 ± 3 (6–22) | 13 ± 3 (6–22)       | 13 ± 3 (6–22)               |
| Tested for APOE ε4 carrier     | 140 (28)      | 30 (55)              | 110 (24)§                   |
| Tested for memory impairmentd  | 81 (15)       | 22 (39)              | 59 (12)§                    |
| Tested for hippocampal atrophy| 88 (20)       | 19 (40)              | 69 (18)§                    |
| β-amyloid level                |               |                      |                             |
| Negative                       | 337 (63)      | 17 (30)              | 320 (67)§                   |
| Uncertain                      | 52 (10)       | 4 (7)                | 48 (11)                     |
| Moderate                       | 51 (10)       | 6 (11)               | 45 (9)                      |
| High                           | 76 (14)       | 21 (37)              | 55 (12)§                    |
| Very high                      | 18 (3)        | 9 (16)               | 9 (2)§                      |
| Time to progression, y         | 3.6 ± 1.8 (1.4–7.6) |                      |                             |
| Length of follow-up, y         | 5.3 ± 1.7 (2.7–8.0) | 5.0 ± 1.7 (2.8–8.0) | 5.4 ± 1.7 (2.7–8.0)         |

Data are presented as mean ± SD (range) or n (% of column total). Differences between progressors and cognitively stable participants were assessed using *independent t test* p < 0.05, †Pearson χ² test, p < 0.01, ‡Fisher exact test p < 0.01. *Defined by California Verbal Test II delayed free recall Z score as ≤ −1.0.*
number (intercept) and time from baseline (slope) were included as random factors. Sex, age, years of education, and APOE\textsuperscript{e4} status were included as covariates. Data from 5 review cycles, approximately equivalent to baseline and 18 months, 36 months, 54 months, and 72 months follow-up, were included in each of the models.

### Data Availability

Most baseline data are available on the AIBL subsection of the adni.loni.usc.edu website. Limited follow-up data are available at this site and access to all the data in this article can be requested through an application to the AIBL management committee.

### Results

#### Baseline Findings

Demographic characteristics of the 534 CN participants are shown in tables 1 and 2. At baseline, the mean age was 72 ± 6 years, 55% were women, 28% were APOE\textsuperscript{e4} positive, and 27% were Aβ scan positive using a threshold of 25 CL. During the follow-up period of 5.3 ± 1.7 years, 57 participants (11%) progressed to MCI or dementia.

Age, APOE\textsuperscript{e4} status, baseline CVLT-II LDFR, and HA were significantly different between the progressors and clinically stable group (table 1). Aβ level (>50 CL) was more prevalent in the progressor group while Aβ level (<15 CL) was more prevalent in the stable group. HA was more prevalent in the progressor group (table 1).

Table 2 shows that the groups with greater Aβ burden were older and had a higher prevalence of APOE\textsuperscript{e4} and HA than the Aβ-negative group.

### Aβ and Clinical Progression

We assessed the effect of the individual factors on clinical progression to MCI or dementia (table 3). By the 4.5-year follow-up time point, 79 (15%) of the stable participants had withdrawn. Their baseline demographics were no different from the whole cohort. In particular, the proportion in each CL

#### Table 2 Characteristics of Participants Based on Centiloid Group

| Centiloid Group | Negative (n = 337) | Uncertain (n = 52) | Moderate (n = 51) | High (n = 76) | Very high (n = 18) |
|-----------------|-------------------|-------------------|------------------|-------------|-------------------|
| Age, y          | 71 ± 6            | 72 ± 4            | 75 ± 6\textsuperscript{b} | 74 ± 6\textsuperscript{b} | 76 ± 6\textsuperscript{b} |
| Female          | 191 (57)          | 25 (48)           | 26 (51)          | 44 (58)     | 9 (50)            |
| Education, y    | 13 ± 3            | 12 ± 3            | 12 ± 3           | 13 ± 3      | 13 ± 3            |
| Tested for memory |                  |                   |                  |             |                   |
| Memory impairment\textsuperscript{f} | 43 (13) | 9 (17) | 13 (25)\textsuperscript{c} | 12 (16) | 4 (22) |
| AIBL-PACC       | 0.21 ± 0.83       | 0.28 ± 0.78       | 0.04 ± 1.02      | −0.15 ± 0.92\textsuperscript{a} | 0.27 ± 1.07 |
| Tested for APOE\textsuperscript{e4} |                  |                   |                  |             |                   |
| APOE\textsuperscript{e4} carrier | 60 (19) | 10 (21) | 23 (46)\textsuperscript{c,d} | 35 (47)\textsuperscript{c,d} | 12 (71)\textsuperscript{d,e} |
| Tested hippocampal volume |                  |                   |                  |             |                   |
| Hippocampal atrophy | 43 (16) | 10 (24) | 11 (26)          | 18 (28)\textsuperscript{d} | 6 (40)\textsuperscript{a} |

Abbreviations: AIBL-PACC = Preclinical AD Cognitive Composite. Data are presented as mean ± SD or n (% of column total). Statistical differences (p < 0.05) between Centiloid groups were assessed using independent \(t\) test compared to negative, independent \(t\) test compared to uncertain, Pearson \(\chi^2\) test compared to negative, Pearson \(\chi^2\) test compared to uncertain, Fisher exact test compared to negative. No other comparisons were significant.\textsuperscript{f} Defined by California Verbal Test II delayed free recall \(Z\) score as ≤−1.0.

#### Table 3 Univariate Cox Regression Hazard Ratio (95% Confidence Interval)

| Factor                          | All MCI or AD | Full Data Set |
|---------------------------------|---------------|---------------|
| Age                             | 1.2 (0.6–2.2) | 1.8 (1.1–3.1)\textsuperscript{p} |
| Male                            | 1.6 (0.9–3.0) | 1.4 (0.8–2.3) |
| Lower education                 | 1.1 (0.6–2.0) | 0.9 (0.5–1.5) |
| CVLT-II LDFR                    | 1.8 (0.8–3.7) | 4.0 (2.4–6.8)* |
| APOE\textsuperscript{e4}        | 3.3 (1.7–6.2)* | 3.3 (1.9–5.6)* |
| Hippocampal atrophy             | 3.1 (1.6–6.1)* | 1.8 (1.0–3.1)* |
| Aβ level                        |               |               |
| Uncertain                       | 1.3 (0.4–4.3) | 1.6 (0.5–4.7) |
| Moderate                        | 0.9 (0.2–4.0) | 3.2 (1.3–7.6)* |
| High                            | 5.2 (2.5–10.5)* | 7.0 (3.7–13.3)* |
| Very high                       | 8.1 (3.1–20.8)* | 11.4 (5.1–25.8)* |

Abbreviations: MCI or AD CVLT-II LDFR Aβ. Data are hazard ratio (95% confidence interval) from univariate Cox regression fitted to each column where \(\ast\) is \(p < 0.001\), \(\ast\) is \(p < 0.05\), age is >72 years, lower education is <13 years, CVLT is <−1.0 SD, and hippocampal atrophy is ≤2.74 cm\textsuperscript{3}.
category was no different (64% negative, 8% uncertain, 10% moderate, 18% high, 0% very high). Beyond the 4.5-year time point, the number at risk in the Aβ-positive groups declined substantially (figure 1). Consequently, progression was assessed at 4.5 years as well as for the full data set. At 4.5 years, carriage of APOE ε4, HA, and positive Aβ scan were associated with significant increase in risk of clinical progression (table 3). Greatest risk was seen with high and very high Aβ levels (HR 5.2 and 8.1, respectively). An uncertain or moderate Aβ PET result did not affect the risk of clinical progression by 4.5 years (HR 1.3 and 0.9, respectively). With the full data set, age greater than 72 years, low baseline memory performance on the CVLT-II LDFR, and moderate Aβ level (26–50 CL) emerged as significant risks. The risk from APOE ε4 carriage was unchanged, the risk from HA declined, and the risk from high and very high Aβ level increased (table 3). Figure 1 illustrates that progression to MCI or dementia in the moderate Aβ level group occurred predominantly after 4.5 years of follow-up.

**Aβ and Cognitive Change**

With sex, age, years of education, and APOE ε4 status as covariates, compared to the negative CL group, the moderate, high, and very high groups showed decline in longitudinal cognitive performance on the AIBL-PACC (moderate −0.02 SD/year, $p = 0.05$; high −0.08 SD/year, $p < 0.001$; and very high −0.35 SD/year, $p < 0.001$) (figure 2). The same was observed for performance on the CVLT-II LDFR (moderate −0.02 SD/year, $p = 0.03$; high −0.1 SD/year, $p < 0.05$; and very high −0.24, $p < 0.05$). On the CDR-SoB, only the high and very high groups performed worse compared to the negative group (high −0.17/y and very high −0.38/y). Practice effects were observed for the negative group on the AIBL-PACC and CVLT-II LDFR (+0.18 SD/year and +0.04 SD/year, respectively). No other significant differences were observed between the groups.

**Discussion**

In this study, we showed that the level of Aβ deposition in the brain could identify CN people at risk for cognitive decline and clinical progression to MCI or dementia and better stratify that risk than binary classification of an Aβ PET scan as just positive or negative. The greatest cognitive decline and rate of clinical disease progression was seen in the participants with an Aβ level higher than 50 CL. Participants with a moderately positive scan of 26–50 CL showed little clinical progression until after 4.5 years of follow-up. We found that the prevalence of MCI or dementia with an average follow-up of 5.3 years was 5% if <15 CL, 7% if 16–25 CL, 12% if 26–50 CL, 28% if 51–100 CL, and 50% if >100 CL. This indicates that the level of Aβ provides important prognostic information.
We have previously reported this observation but only in patients with $^{11}$C-PiB PET quantified with SUVR using in-house–derived regions of interest. Consequently, the findings could not be easily translated into clinical practice. In the present larger study, we used the CL scale to allow inclusion of participants imaged with a variety of Aβ tracers ($^{11}$C-PiB in 44%, $^{18}$F-florbetapir in 27%, $^{18}$F-flutemetamol in 29%) and to stratify the level of Aβ into categories that can be replicated in any clinical or research PET site, purposes for which the CL method was developed. The close match of our cohort characteristics, including age, prevalence of APOE ε4, proportion with positive Aβ PET, and clinical progression rate in the Aβ-positive participants, with other longitudinal studies of older CN cohorts suggests that our findings are widely applicable. For example, in our cohort, the risk of progression to MCI or dementia over a mean of 5.3 years of follow-up was 25% in Aβ-positive CN defined as >25 CL. This is consistent with progression rates for Aβ-positive CN in the Mayo Clinic Study of Aging (18% at 3.7 years), the Alzheimer’s Disease Neuroimaging Initiative (ADNI) (32% at 4 years), the Washington University Knight Alzheimer Disease Research Center (26% at 5 years), and the Harvard Aging Brain Study (20% at 3 years). Our study is unique in that it has demonstrated that the level of Aβ deposition in a positive Aβ scan provides additional prognostic information.

Our findings also have implications for preclinical AD therapeutic trials if slowing or halting cognitive decline is the proposed primary outcome measure. Suitable participants for such trials must be at high risk for detectable cognitive decline over the period of the study. Figure 2 suggests by separation of the confidence limits that the groups with high or very high Aβ burden (i.e., >50 CL) have significantly declined compared to the Aβ-negative group on several cognitive measures within 3 years of follow-up. In contrast, those with a moderate Aβ burden declined much less compared to baseline performance, with minimal change and no increased risk of progression to MCI or dementia at 4.5 years (HR 0.9). This suggests that in a preclinical AD trial time frame of 3 to 4 years, therapeutic benefit may be better assessed in CN with <50 CL of Aβ by change in disease biomarkers rather than by slowing of cognitive decline.

In this study, we examined several measures known to be predictive of clinical progression in older CN adults. Low score on the baseline CVLT-II LDFR posed a moderate risk for clinical progression, though this may be a partly circular argument as low cognitive scores are a key component of a clinical diagnosis of MCI. As expected, APOE ε4 carriage was associated with a 3-fold increase in risk of clinical progression. The effect of ε4 may be indirect, as APOE ε4 is associated with greater prevalence of AD and earlier disease onset so that at a given age, ε4 carriers have more advanced disease and higher Aβ levels. We found no effect of sex on progression risk. Other studies suggest that AD is more prevalent in women and females have a greater risk of clinical progression from MCI to AD dementia. More research is needed on the effect of sex differences in the preclinical phase of the development of AD. HA predicts clinical progression to dementia and can discriminate patients with MCI from controls. In this study, the individuals with HA also had greater risk for progression. High and very high Aβ level had the
largest HRs for progression of any of the factors examined, reaching 8.1 in the very high group and 11.4 in the full data set. The very high Aβ group had the highest prevalence of HA and APOE ε4, both of which are consistent with longer disease duration and a more advanced preclinical stage of AD at the time of initial assessment.

We did not examine for interaction with other factors that may alter risk of disease progression in preclinical AD. This includes comparison to the ATN (Aβ, tau, neurodegeneration) classification scheme as tau measures were not available at baseline in this cohort. Previous analysis of longitudinal data from AIBL reported that rate of decline on cognitive test scores in CN with positive Aβ PET was greater in those who were APOE ε4 carriers but this was not found in ADNI or BioFINDER. Extrapolation of our findings to an individual should be approached with caution. Aβ PET imaging of asymptomatic individuals other than for clinical trial screening is not recommended by the Society of Nuclear Medicine/Alzheimer’s Association Amyloid Imaging Task Force. Although we have demonstrated that risk of clinically significant decline in CN older individuals is strongly related to the degree of Aβ burden, the value of this prognostic information remains unclear in the absence of effective treatment. Although the CL method provides a standardized measure of brain Aβ burden, the results can differ slightly between laboratories due to factors such as PET camera make and model and local modifications to the standard CL method, some of which show tracer-dependent variance. Provided appropriate corrections have been made for modified methods, any residual variation between laboratories should not affect the conclusions of this study as they are based on groups with a broad range of CL. A limitation of all longitudinal studies is the withdrawal of participants over time. At 4.5 years, 15% of the stable cohort had withdrawn or not reached this time point. Their baseline demographics matched the entire cohort so this is unlikely to affect the study findings. The participant retention rate in this study compares well to other longitudinal studies.

The level of Aβ deposition is important for the prediction of progression to MCI or dementia. This study provides evidence that the currently used binary classification of positive or negative for the reporting of an Aβ scan is suboptimal for determination of prognosis in CN older individuals. Aβ level stratified by CL-defined groupings provides greater individual prognostic information and should assist design of therapeutic trials in preclinical AD.

Acknowledgment
The authors thank the participants who took part in the study as well as their families.

Study Funding
Core funding for the study was provided by the CSIRO Flagship Collaboration Fund and the Science and Industry Endowment Fund in partnership with Austin Health, University of Melbourne, Edith Cowan University, Florey Institute of Neuroscience and Mental Health, Alzheimer’s Australia, and the National Ageing Research Institute. The study also received funding from the National Health and Medical Research Council, the Dementia Collaborative Research Centres program, the McCusker Alzheimer’s Research Foundation, and Operational Infrastructure Support from the Government of Victoria.

Disclosure
L. van der Kall and T. Truong report no disclosures. S.C. Burnham reports a patent, “Method for detection of a neurologic disease,” issued to CSIRO. V. Doré, R.S. Mulligan, S. Bozinovski, and F. Lamb report no disclosures. P. Bourgeat reports a patent, “Method for detection of a neurologic disease,” issued to CSIRO. J. Robertson reports no disclosures. V. Villemagne is supported by an NHMRC Senior Research Fellowship. C. Rowe is supported by an NHMRC Practitioner Fellowship (1140853) and has received research support from GE Healthcare, Avid Radiopharmaceuticals, and the National Health and Medical Research Council of Australia (1152623, 1132604, 1071430, 1011689). Go to Neurology.org/N for full disclosures.

Publication History
Received by Neurology August 13, 2019. Accepted in final form September 24, 2020.

Appendix Authors

| Name                  | Location                    | Contributions                                                                 |
|-----------------------|-----------------------------|-------------------------------------------------------------------------------|
| Laura M. van der Kall, MSc | Austin Health, Melbourne, Australia | Designed and conceptualized study, analysed the data, drafted the manuscript |
| Thanh Truong, BH-BMed | Austin Health; University of Melbourne, Australia | Analysed the data, drafted the manuscript, interpretation of the data |
| Samantha C. Burnham, PhD | CSIRO, Melbourne, Australia | Statistical design, interpretation of the data, revision of manuscript |
| Vincent Doré, PhD     | CSIRO, Melbourne, Australia | Acquisition of the data, interpretation of the data, revision of manuscript |
| Rachel S. Mulligan, PhD | Austin Health, Melbourne, Australia | Data acquisition |
| Svetlana Bozinovski, RN | Austin Health, Melbourne, Australia | Administrative support |
### References

1. Jack CR Jr, Knopman DS, Jagust WJ, et al. Tracking pathophysiological processes in Alzheimer’s disease: an updated hypothetical model of dynamic biomarkers. Lancet Neurol 2013;12:207–216.

2. Villemagne VL, Burnham S, Bourgeat P, et al. Amyloid beta deposition, neurodegeneration, and cognitive decline in sporadic Alzheimer’s disease: a prospective cohort study. Lancet Neurol 2013;12:357–367.

3. Budgeon CA, Murray K, Turlach BA, et al. Constructing longitudinal disease progression curves using sparse, short-term individual data with an application to Alzheimer’s disease. Stat Med 2017;36:2720–2734.

4. Sperling RA, Aisen PS, Beckett LA, et al. Toward defining the preclinical stages of Alzheimer’s disease: recommendations from the National Institute on Aging- Alzheimer’s Association workgroups on diagnostic guidelines for Alzheimer’s disease. Alzheimers Demen 2011;7:280–292.

5. Chetelat G, Villemagne VL, Pike KE, et al. Independent contribution of temporal beta-amyloid deposition to memory decline in the pre-dementia phase of Alzheimer’s disease. Brain 2011;134:799–807.

6. Ellis KA, Lim YY, Harrington K, et al. Decline in cognitive function over 18 months in healthy older adults with high amyloid-beta. J Alzheimers Dis 2013;34:861–871.

7. Jack CR Jr, Bennett DA, Blennow K, et al. NIA-AA Research Framework: toward a biological definition of Alzheimer’s disease. Alzheimers Dement 2018;14:533–562.

8. Villemagne VL, Pike KE, Chetelat G, et al. Longitudinal assessment of Abeta and cognition in aging and Alzheimer disease. Ann Neurol 2011;69:181–192.

9. Doraiswamy PM, Sperling RA, Coleman RE, et al. Amyloid-beta assessed by florbetapir F 18 PET and 18-month cognitive decline: a multicenter study. Neurology 2012;79:1636–1644.

10. Dang C, Harrington KD, Lim YY, et al. Relationship between amyloid beta positivity and progression to mild cognitive impairment or dementia over 8 years in cognitively normal older adults. J Alzheimers Dis 2018;65:1313–1325.

11. Rowe CC, Bourgeat P, Ellis KA, et al. Predicting Alzheimer disease with beta-amyloid imaging: results from the Australian imaging, biomarkers, and lifestyle study of ageing. Ann Neurol 2013;74:905–913.

12. Klunk WE, Koepp RA, Price JC, et al. The Centiloid project: standardizing quantitative amyloid plaque estimation by PET. Alzheimers Dement 2015;11:e1–15.e11–e14.

13. Rowe CC, Jones G, Dore V, et al. Standardized expression of HF-NAV4694 and 11C-PiB beta-amyloid PET results with the centiloid scale. J Nucl Med 2016;57:1233–1237.

14. Battle MR, Pillay LC, Lowe VJ, et al. Centiloid scaling for quantification of brain amyloid with [18F]fluorotimelamet using multiple processing methods. JNMMI Res 2018;8:107.

15. Rowe CC, Dore V, Jones G, et al. 15F-Florbetaben PET beta-amyloid binding expressed in Centiloids. Eur J Nucl Med Mol Imaging 2017;44:2053–2059.

16. La Joie R, Akayta N, Seeley WW, et al. Multisite study of the relationships between antemortem [11C]PiB-PET Centiloid values and postmortem measures of Alzheimer’s disease neuropathology. Alzheimers Dement 2019;15:205–216.

17. Navitsky M, Joshi AD, Kennedy L, et al. Standardization of amyloid quantitation with florbetapir standardized uptake value ratios at the Centiloid scale. Alzheimers Dementia 2018;14:1565–1571.

18. Dore V, Bullich S, Rowe CC, et al. Comparison of 18F-florbetaben quantification results using MR-based and MR-less CapAIBL validation against histopathology. Alzheimers Dementia 2019;15:807–816.

19. Amadoro S, Dore V, McLean CA, et al. Comparison of amyloid PET measured in Centiloid units with neuropathological findings in Alzheimer’s disease. Alzheimers Res Ther 2020;12:22.

20. Ellis KA, Bush AI, Darby D, et al. The Australian Imaging, Biomarkers and Lifestyle (AI BL) study of aging: methodology and baseline characteristics of 1112 individuals recruited for a longitudinal study of Alzheimer’s disease. Int Psychogeriatr 2009;21:672–687.

21. Winblad B, Palmer K, Krupelito M, et al. Mild cognitive impairment–beyond controversies, towards a consensus: report of the international working group on mild cognitive impairment. J Intern Med 2004;255:240–246.

22. McKhann G, Drachman D, Folstein M, Katzman R, Price D, Stadlan EM. Clinical diagnosis of Alzheimer’s disease: report of the NINCDS-ADRDA Work Group under the auspices of Department of Health and Human Services Task Force on Alzheimer’s Disease. Neurology 1984;34:939–944.

23. Donohue MC, Sperling RA, Salmon DP, et al. The preclinical Alzheimer cognitive composite: measuring amyloid-related decline. JAMA Neurology 2014;71:961–970.

24. Bourgeat P, Villemagne VL, Dore V, et al. Comparison of MR-less PiB SUVR quantification methods. Neurobiol Aging 2015;36:S159–S166.

25. Bourgeat P, Dore V, Fripp J, et al. Implementing the centiloid transformation for 11C-PiB and j-amyloid 18F PET tracers using CapAIBL. Neuroimage 2018;181:387–393.

26. Bourgeat P, Dore V, Shen K, Raniga P, Salvado O, Fripp J. Enforcing Longitudinal Consistency in Longitudinal analysis using multi-atlas segmentation. Presented at: MICCAI 2012 Workshop on Novel Imaging Biomarkers for Alzheimer’s Disease and Related Disorders, Nice, France, October 5, 2012.

27. Insel PS, Weiner M, Mackin RS, et al. Determining clinically meaningful decline in preclinical Alzheimer’s disease. Neurology 2019;93:e322–e333.

28. Roberts RO, Aakee JA, Kremers WE, et al. Prevalence and outcomes of amyloid positivity among persons without dementia in a longitudinal, population-based setting. JAMA Neurol 2018;75:970–979.

29. Donohue MC, Sperling RA, Petersen R, et al. Association between elevated brain amyloid and subsequent cognitive decline among cognitively normal persons. JAMA Neurol 2017;74:23–33.

30. Papp KV, Buckley R, Mormino E, et al. Clinical meaningfulness of subtle cognitive decline in longitudinal testing in preclinical AD. Alzheimers Dementia 2020;16:552–560.
32. Fleisher AS, Sowell BB, Taylor C, et al. Clinical predictors of progression to Alzheimer disease in amnestic mild cognitive impairment. Neurology 2007;68:1588–1595.
33. Hollands S, Lim YY, Laws SM, et al. APOE-epsilon4 genotype, amyloid, and clinical disease progression in cognitively normal older adults. J Alzheimers Dis 2017;57:411–422.
34. Prince M, Ali GC, Guerchet M, Prina AM, Albanese E, Wu YT. Recent global trends in the prevalence and incidence of dementia, and survival with dementia. Alzheimers Res Ther 2016;8:23.
35. Lin KA, Choudhury KR, Rathakrishnan BG, et al. Marked gender differences in progression of mild cognitive impairment over 8 years. Alzheimers Dement 2015;1:103–110.
36. Gao S, Hendrie HC, Hall KS, Hui S. The relationships between age, sex, and the incidence of dementia and Alzheimer disease: a meta-analysis. Arch Gen Psychiatry 1998;55:809–815.
37. Henneman WJP, Skiriner JD, Barnes J, et al. Hippocampal atrophy rates in Alzheimer disease: added value over whole brain volume measures. Neurology 2009;72:999–1007.
38. Lim YY, Kalinowski P, Pietrzak RH, et al. Association of β-Amyloid and apolipoprotein E e4 with memory decline in preclinical Alzheimer disease. JAMA Neurol 2018;75:488–494.
39. Johnson KA, Minoshima S, Bohnen NI, et al. Appropriate use criteria for amyloid PET: a report of the Amyloid Imaging Task Force, the Society of Nuclear Medicine and Molecular Imaging, and the Alzheimer’s Association. Alzheimers Dement 2013;9:e1–e16.
Association of β-Amyloid Level, Clinical Progression, and Longitudinal Cognitive Change in Normal Older Individuals
Laura M. van der Kall, Thanh Truong, Samantha C. Burnham, et al.
Neurology 2021;96:e662-e670 Published Online before print November 12, 2020
DOI 10.1212/WNL.0000000000011222

This information is current as of November 12, 2020
Author/s:
Van der Kall, LM; Thanh, T; Burnham, SC; Dore, V; Mulligan, RS; Bozinovski, S; Lamb, F; Bourgeat, P; Fripp, J; Schultz, S; Lim, YY; Laws, SM; Ames, D; Fowler, C; Rainey-Smith, SR; Martins, RN; Salvado, O; Robertson, J; Maruff, P; Masters, CL; Villemagne, VL; Rowe, CC

Title:
Association of beta-Amyloid Level, Clinical Progression, and Longitudinal Cognitive Change in Normal Older Individuals

Date:
2021-02-02

Citation:
Van der Kall, L. M., Thanh, T., Burnham, S. C., Dore, V., Mulligan, R. S., Bozinovski, S., Lamb, F., Bourgeat, P., Fripp, J., Schultz, S., Lim, Y. Y., Laws, S. M., Ames, D., Fowler, C., Rainey-Smith, S. R., Martins, R. N., Salvado, O., Robertson, J., Maruff, P. ..., Rowe, C. C. (2021). Association of beta-Amyloid Level, Clinical Progression, and Longitudinal Cognitive Change in Normal Older Individuals. NEUROLOGY, 96 (5), pp.E662-E670. https://doi.org/10.1212/WNL.0000000000011222.

Persistent Link:
http://hdl.handle.net/11343/274443

File Description:
Published version

License:
CC BY-NC-ND