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Citation
Lee, S., M. E. Zimmerman, A. Narkhede, S. E. Nasrabady, G. Tosto, I. B. Meier, T. L. S. Benzinger, et al. 2018. “White matter hyperintensities and the mediating role of cerebral amyloid angiopathy in dominantly-inherited Alzheimer’s disease.” PLoS ONE 13 (5): e0195838. doi:10.1371/journal.pone.0195838.

Published Version
doi:10.1371/journal.pone.0195838

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Accessibility
White matter hyperintensities and the mediating role of cerebral amyloid angiopathy in dominantly-inherited Alzheimer’s disease

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Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Funding: This work was supported by NIH/NIA U19 AG032438. SL is supported by NIH/NIA AG051348. This work was supported by the German Center for Neurodegenerative Diseases (DZNE), Raul Carrea Institute for Neurological Research (FLENI), with partial support by the Research and Development Grants for Dementia

OPEN ACCESS

Citation: Lee S, Zimmerman ME, Narkhede A, Nasrabady SE, Tosto G, Meier IB, et al. (2018) White matter hyperintensities and the mediating role of cerebral amyloid angiopathy in dominantly-inherited Alzheimer’s disease. PLoS ONE 13(5): e0195838. https://doi.org/10.1371/journal.pone.0195838

Editor: Stephen D. Ginsberg, Nathan S Kline Institute, UNITED STATES

Received: October 16, 2017
Accepted: April 1, 2018
Published: May 9, 2018

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Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Funding: This work was supported by NIH/NIA U19 AG032438. SL is supported by NIH/NIA AG051348. This work was supported by the German Center for Neurodegenerative Diseases (DZNE), Raul Carrea Institute for Neurological Research (FLENI), with partial support by the Research and Development Grants for Dementia

PLOS ONE | https://doi.org/10.1371/journal.pone.0195838 May 9, 2018 1 / 15
Abstract

Introduction
White matter hyperintensity (WMH) volume on MRI is increased among presymptomatic individuals with autosomal dominant mutations for Alzheimer’s disease (AD). One potential explanation is that WMH, conventionally considered a marker of cerebrovascular disease, are a reflection of cerebral amyloid angiopathy (CAA) and that increased WMH in this population is a manifestation of this vascular form of primary AD pathology. We examined whether the presence of cerebral microbleeds, a marker of CAA, mediates the relationship between WMH and estimated symptom onset in individuals with and without autosomal dominant mutations for AD.

Participants and methods
Participants (n = 175, mean age = 41.1 years) included 112 with an AD mutation and 63 first-degree non-carrier controls. We calculated the estimated years from expected symptom onset (EYO) and analyzed baseline MRI data for WMH volume and presence of cerebral microbleeds. Mixed effects regression and tests of mediation were used to examine microbleed and WMH differences between carriers and non-carriers and to test the whether the association between WMH and mutation status is dependent on the presence of microbleeds.

Results
Mutation carriers were more likely to have microbleeds than non-carriers (p < 0.05) and individuals with microbleeds had higher WMH volume than those without (p < 0.05). Total WMH volume was increased in mutation carriers compared with non-carriers, up to 20 years prior to EYO, after controlling for microbleed status, as we demonstrated previously. Formal testing of mediation demonstrated that 21% of the association between mutation status and WMH was mediated by presence of microbleeds (p = 0.03) but a significant direct effect of WMH remained (p = 0.02) after controlling for presence of microbleeds.

Discussion
Although there is some co-dependency between WMH and microbleeds, the observed increases in WMH among mutation carriers does not appear to be fully mediated by this marker of CAA. The findings highlight the possibility that WMH represent a core feature of AD independent of vascular forms of beta amyloid.

Introduction
There is an emerging interest in the role of small vessel cerebrovascular changes in late onset Alzheimer’s disease (AD). While there is general agreement that small vessel cerebrovascular disease contributes independently to the clinical presentation of AD by lowering clinical diagnostic thresholds or conferring additive cognitive impairment, there is considerable controversy
about whether it plays a primary role in AD pathogenesis, representing a core feature of the disease. The study of the contribution of small vessel cerebrovascular disease to late onset AD is difficult because the ordering and timing of the onset of biological changes is obscured by a potentially decades-long preclinical period[1] and confounded by its strong association with age and vascular risk factors, such as hypertension. We addressed these issues previously by turning to the Dominantly Inherited Alzheimer’s Network (DIAN) study[1, 2], which enrolls individuals at 50% risk for developing AD, typically early onset, by virtue of having a first-degree relative with an autosomal dominant, fully-penetrant genetic mutation for AD. We quantified small vessel cerebrovascular disease as the regional volume of white matter hyperintensities (WMH), areas of increased signal on T2-weighted magnetic resonance imaging (MRI), that may reflect ischemic injury[3] or other mechanisms. Increased WMH volume, particularly when distributed in posterior regions, is associated with increased risk for late onset AD and with the severity and course of the disease[4]. In DIAN, we modeled WMH severity and distribution in mutation carriers and non-carriers as a function of the estimated years to symptom onset (EYO), defined as the difference between the age of the affected first-degree relative’s age of symptom onset and the participant’s age[2]. We found that mutation carriers had reliably increased WMH volume, particularly in posterior regions, which appeared elevated as much as 22 years prior to symptom onset. We concluded that WMH burden is a distinct core feature of AD that should be considered explicitly in models of disease pathogenesis.

One outstanding issue regarding these findings relates to the presence of cerebral amyloid angiopathy (CAA), the vascular deposition of amyloid pathology. Cerebral amyloid angiopathy can cause small hemorrhagic lesions, or microbleeds, that manifest as punctate hypointense voids on gradient echo (GRE) sequences[5]. Previous work showed a relationship of WMH volume, particularly in posterior areas, with cerebral microbleeds[6] and that individuals with familiar forms of AD have comparable frequencies of microbleeds to those with late onset disease[7, 8]. The question of the extent to which CAA mediates the observed relationship between WMH and AD is critical: if WMH in the context of AD is driven by CAA, then prevention or intervention strategies could focus on vascular forms of amyloid pathology. However, if the association of WMH with AD is independent of CAA, then other mechanisms or forms of vascular pathology (e.g., ischemia, blood brain barrier damage, inflammation-mediated, etc.) become highly relevant in the conceptualization of disease pathogenesis and strategies for intervention or prevention. The purpose of this study was to examine the role of CAA, operationally-defined as the presence of cerebral microbleeds on GRE MRI, in the context of autosomal dominant AD and in the relationship we observed previously between WMH and autosomal dominant mutation status.

**Materials and methods**

**DIAN study**

The Dominantly Inherited Alzheimer’s Network (www.dian-info.org; NIA-U19-AG032438) is a multisite effort that includes centers in the United States, UK, Germany, Australia, Japan, Korea, and Argentina. DIAN participants are from families with a known autosomal-dominant mutation for AD, including APP, PSEN1, and PSEN2, irrespective of their own mutation status. As part of the DIAN, participants receive a baseline assessment with sampling of blood and CSF, clinical assessment, neuropsychological evaluation, and neuroimaging and are followed longitudinally with identical assessments. Full procedures for the study are described elsewhere[1, 9]. All assessment and imaging procedures were approved by the Washington University Human Research Protection Office. All participants gave written informed consent according to the Declaration of Helsinki. Local institutional review boards/ethics committees
Clinical assessment
Clinical assessments were performed by individuals who were unaware of each participant’s mutation status. The evaluation included neuropsychological testing, medical examination, administration of the Clinical Dementia Rating (CDR) scale[10], and determination of the parental age of onset. A semi-structured interview, which determined the age at which the affected parent started exhibiting symptoms, was used to determine parental age at onset[1, 2]. The difference between the participant’s age and the parental age at onset was used to establish the EYO. The EYO variable was calculated for all participants regardless of their mutation status. Participants with negative EYO are younger than their parental age at onset. Data included here were a subset from Data Freeze 6.

MRI image processing
Baseline MRI data were analyzed for WMH volume on T2-weighted FLAIR scans (repetition time: 9,000; echo time: 90; voxel dimensions: 0.86 x 0.86 x 5.0 mm) and for presence and number of cerebral microbleeds, a radiological marker of CAA, on T2-weighted scans (repetition time: 650; echo time: 20; voxel dimensions: 0.78 x 0.78 x 5.0 mm). White matter hyperintensity quantification in this cohort has been described previously[2]. Briefly, an algorithm that labeled voxel intensity values above a study-specific threshold was applied to each individual FLAIR image; the number of voxels labeled with this approach were summed and multiplied by voxel dimensions to yield total WMH volumes for each participants. We also co-registered a “lobar” atlas to each image to derive the WMH volume in the frontal, temporal, parietal, and occipital lobes. Because the values were not normally distributed, total and regional WMH volumes were transformed with inverse hyperbolic sine. Fig 1 displays an example of a participant with prominent posterior WMH.

Microbleeds, sometimes referred to as “microhemorrhages,” were identified on GRE images following procedures that have been described previously (85% interrater agreement, κ = 68%) [11]. Briefly, expert operators visually inspected each image and rated microbleeds as homogeneous hypointense lesions up to 10 mm in diameter in grey or white matter. We dichotomized the participants into those with (present) and without (absent) one or more cerebral microbleeds for statistical analyses. Fig 1 displays an example of a cerebral microbleed in a DIAN participant.

Statistical analysis
SAS (version 9.4) was used for all statistical analyses. Demographic and clinical variables were compared by microbleed status with Wilcoxon’s test and chi-squared analysis for continuous and categorical variables, respectively. We also tested whether the difference between those with and without microbleeds persisted after controlling for EYO and CDR-Sum-of-boxes (CDR-SB) using linear regression and logistic regressions for continuous and categorical...
variables. We used linear mixed-effect regression analysis to test whether WMH volume differed by mutation type and microbleed status, controlling for participant family as a random effect.

We also tested whether there is inflection point in microbleed status by the EYO using piece-wise generalized linear mixed-effect regression. The final models were selected using

![Fig 1. Examples of WMH and microbleeds.](https://doi.org/10.1371/journal.pone.0195838.g001)

![Fig 2. Mediation models.](https://doi.org/10.1371/journal.pone.0195838.g002)
Bayesian information criteria as described elsewhere[2]. The same inflection point analyses were carried out for WMH volume with and without microbleed status as a covariate.

Two models described in Fig 2 were tested for the primary hypotheses. Model 1 tested whether microbleed status is in the causal pathway between mutation status and WMH volume using mediation analysis. Model 2 tested whether the relationships between mutation status, microbleed status, and WMH volume differ by EYO (moderation). We separately tested whether three paths (between mutation status and WMH, between mutation status and microbleed status, and between microbleed status and WMH) differ by EYO. We did not find significant moderation effect of EYO on the association between microbleed status and WMH volume. Thus, in the final model, the moderation effect on the association between microbleed status and WMH volume was omitted. Based on causal effects models[12–14], the mediation (or indirect) effect explained by microbleed status was estimated as the difference between the total effect of mutation status on WMH and direct effect of mutation status on WMH volume controlling for microbleed status. For statistical inference, bootstrapping was used to derive 95% confidence intervals of the total, direct, and indirect effects. All models were adjusted for APOE-ε4 status, EYO and age. Models were also re-run with CDR-SB as a covariate and in the subset of participants with CDR-SB scores of less than or equal to 0.5 (n = 138) and after excluding individuals with APP mutations (n = 37) because of known associations between APP and CAA[15].

As a secondary exploratory analysis, we tested the same mediation and moderated-mediation of the number of microbleeds on the relationship between mutation status and WMH volume in the participants with one or more microbleeds (n = 26). The number of microbleeds was log-transformed to reduce skewness.

**Results**

**Participants**

One hundred seventy-five participants had both WMH measures and GRE MRI scans with derived data of microbleed status. There were 112 mutation carriers of whom 34 (30%) had CDR-SB scores greater than 1, indicating some degree of manifest symptomatology. There was a positive association between CDR-SB and EYO (spearman’s correlation ρ = 0.55, p < 0.0001) within the 112 mutation carriers, indicating that CDR-SB scores increased with closer proximity to the estimated time of symptom onset.

**Microbleeds**

Data comparing those with and without microbleeds are presented in Table 1. Among the 175 participants, 26 participants (15%) had at least one microbleed. Thirteen of 26 participants (50%) had one microbleed, 12 participants had 2–29 microbleeds and one participant had 135 microbleeds. Individuals with microbleeds were 4.6 years older, 4.5 years closer to the estimated age of onset, and had 1.61 points higher CDR-SB scores than the 146 participants without microbleeds. These 26 participants had a more severe biomarker profile than those without, including increased total WMH and WMH volume in temporal, parietal, and occipital lobes, and decreased CSF Aβ1–42, and CSF Aβ1-42/tau ratio values. These differences persisted after controlling for EYO and CDR-SB, except for the difference in CSF Aβ1-42/tau ratio values. Mutation carriers were more likely to have microbleeds than non-carriers (19.6% vs. 6.3%, Fisher’s exact test p = 0.025). This association remained significant (OR = 4.87, 95% CI: 1.16,20.51; p = 0.0334) after adjustment for age, EYO and APOE-ε4 status. Age and APOE-ε4 status were not associated with microbleed status (all p’s >0.15).
We also tested whether the proportion of individuals with microbleeds varied as a function of EYO (i.e., an inflection point). Based on Bayesian information criteria, we did not find evidence of an inflection point in microbleed frequency; the difference in frequency of microbleed status between mutation carriers and non-carriers as a function of EYO was not significant ($p = 0.36$), although mutation carriers more likely have microbleeds than non-carriers ($p = 0.02$). The distribution of the microbleed status by EYO group is found in S1 Table.

White matter hyperintensity volume

In this sub-sample of individuals with available microbleed data, we found a similar pattern of differences in WMH volume between mutation carriers and non-carriers as we reported previously[2]: mutation carriers had elevated total and regional WMH, which appeared to diverge approximately 20 years prior to EYO. This pattern remained even after controlling for microbleed status. Presence of microbleeds was associated with increased regional and total WMH volume (Table 2).

Mediation analysis

Individuals with microbleeds had higher total and regional, including temporal, parietal, and occipital WMH volumes than those without microbleeds (Table 1, Fig 3). The 95% confidence intervals of total, direct, and indirect effects were estimated from 1,000 bootstrapped samples. We found that the higher total WMH volume among mutation carriers (total effect, $p = 0.0009$) was not significantly mediated by microbleed status (indirect effect, $p = 0.1389$)

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**Table 1. Demographic, clinical, and biomarker data in microbleed presence and absence.**

|                          | All (n = 175) | Microbleed Absent (n = 149) | Microbleed Present (n = 26) | p-value |
|--------------------------|--------------|----------------------------|----------------------------|---------|
| Mutation Carriers, n (%) | 112 (64.00)  | 90 (60.4)                  | 22 (84.62)                 | 0.0252  |
| Age, mean years±SD       | 41.05±9.66   | 40.36±9.43                 | 45.00±10.19                | 0.0234  |
| EYO, mean years±SD       | -5.14±9.32   | -5.81±9.29                 | -1.31±8.70                 | 0.0227  |
| Women, n (%)              | 100 (57.14)  | 87 (58.39)                 | 13 (50)                    | 0.5204  |
| Vascular factors (%)      |              |                            |                            |         |
| Hypertension              | 20 (11.43)   | 15 (10.07)                 | 5 (19.23)                  | 0.1854  |
| Hypercholesterolemia      | 27 (15.61)   | 21 (14.29)                 | 6 (23.08)                  | 0.2508  |
| Diabetes                  | 2 (1.14)     | 1 (0.67)                   | 1 (3.85)                   | 0.2758  |
| Smoke                     | 73 (41.71)   | 65 (43.62)                 | 8 (30.77)                  | 0.2826  |
| CDR-SB±SD                 |              |                            |                            |         |
| 1.03±2.31                 | 0.79±2.15    | 2.40±2.77                  | 0.0009                     |
| APOE-ε4+, n (%)           | 55 (31.43)   | 49 (32.89)                 | 6 (23.08)                  | 0.3685  |
| WMH, mean IHS±SD          |              |                            |                            |         |
| Frontal                   | 0.20±0.47    | 0.15±0.25                  | 0.49±1.03                  | 0.1065  |
| Temporal*                 | 0.08±0.29    | 0.04±0.12                  | 0.32±0.65                  | 0.0370  |
| Parietal*                 | 0.16±0.53    | 0.08±0.22                  | 0.60±1.19                  | 0.0357  |
| Occipital*                | 0.23±0.42    | 0.18±0.29                  | 0.54±0.78                  | 0.0261  |
| Total*                    | 0.59±0.79    | 0.49±0.57                  | 1.13±1.44                  | 0.0338  |
| CSF Aβ1-42±SD             | 328.94±153.50| 349.5±148.31               | 196.74±118.68              | <.0001  |
| CSF ptau181±SD            | 57.55±38.94  | 55.2±38.78                 | 71.9±37.73                 | 0.0752  |
| CSF Aβ1-42:tau ratio ±SD  | 5.42±4.98    | 5.91±5.09                  | 2.32±2.61                  | <.0001  |

*aAvailable for n = 141.*

*bAvailable for n = 144.*

*p<0.05;

**p<0.001

https://doi.org/10.1371/journal.pone.0195838.t001
although it explained approximately 20% of the total effect. Similar patterns were found for the regional WMH volumes (see Table 3). The effect of mutation was moderated by EYO (total effect of EYO*Mutation: p’s<0.05) except for frontal WMH, which had trend level significance (p = 0.05), but there was no significant moderated mediation (indirect effect of EYO*Mutation, p’s>0.29) (Table 4). These findings persist even after controlling for CDR-SB (S2 Table). Similar results were found in the subset of CDR-SB is less and equal than 0.5 (S3 Table) and after excluding APP participants (S4 Table).

Table 2. Mixed effect regression coefficients for total and regional WMH volumes and CSF biomarkers.

| Outcome                  | Effect                      | Estimate | S.E. | DF  | t Value | p-value |
|--------------------------|-----------------------------|----------|------|-----|---------|---------|
| Frontal lobe WMH volume  | Intercept                   | -0.082   | 0.24 | 79  | -0.34   | 0.7342  |
|                          | Mutation, Carriers          | 0.153    | 0.083| 89  | 1.84    | 0.0688  |
|                          | Microbleed present*         | 0.299    | 0.099| 89  | 3.01    | 0.0034  |
|                          | EYO                         | -0.007   | 0.007| 89  | -0.99   | 0.3255  |
|                          | EYO* Mutation               | 0.009    | 0.007| 89  | 1.24    | 0.2181  |
|                          | AGE                         | 0.003    | 0.005| 89  | 0.56    | 0.58    |
|                          | APOE-ε4, Positive           | 0.064    | 0.074| 89  | 0.86    | 0.3925  |
| Temporal lobe WMH volume | Intercept                   | -0.177   | 0.148| 79  | -1.2    | 0.2354  |
|                          | Mutation, Carriers          | 0.097    | 0.049| 89  | 1.98    | 0.0507  |
|                          | Microbleed present**        | 0.241    | 0.059| 89  | 4.09    | <.0001  |
|                          | EYO                         | -0.004   | 0.004| 89  | -0.89   | 0.3733  |
|                          | EYO* Mutation               | 0.006    | 0.004| 89  | 1.28    | 0.2044  |
|                          | AGE                         | 0.004    | 0.003| 89  | 1.17    | 0.2434  |
|                          | APOE-ε4, Positive           | -0.021   | 0.044| 89  | -0.47   | 0.6372  |
| Parietal lobe WMH volume | Intercept                   | -0.243   | 0.268| 79  | -0.91   | 0.3669  |
|                          | Mutation, Carriers          | 0.197    | 0.09 | 89  | 2.18    | 0.0319  |
|                          | Microbleed present**        | 0.448    | 0.108| 89  | 4.14    | <.0001  |
|                          | EYO                         | -0.004   | 0.007| 89  | -0.5    | 0.62    |
|                          | EYO* Mutation               | 0.009    | 0.008| 89  | 1.08    | 0.281   |
|                          | AGE                         | 0.005    | 0.006| 89  | 0.84    | 0.4051  |
|                          | APOE-ε4, Positive           | 0.012    | 0.081| 89  | 0.15    | 0.8792  |
| Occipital lobe WMH volume| Intercept                   | -0.119   | 0.22 | 79  | -0.54   | 0.5884  |
|                          | Mutation, Carriers          | 0.223    | 0.072| 89  | 3.08    | 0.0027  |
|                          | Microbleed present**        | 0.28     | 0.087| 89  | 3.23    | 0.0017  |
|                          | EYO                         | -0.004   | 0.006| 89  | -0.68   | 0.4992  |
|                          | EYO* Mutation               | 0.011    | 0.006| 89  | 1.68    | 0.0974  |
|                          | AGE                         | 0.004    | 0.005| 89  | 0.81    | 0.4186  |
|                          | APOE-ε4, Positive           | -0.001   | 0.066| 89  | -0.01   | 0.9904  |
| Total WMH volume         | Intercept                   | 0.127    | 0.418| 79  | 0.3     | 0.762   |
|                          | Mutation, Carriers          | 0.421    | 0.136| 89  | 3.08    | 0.0027  |
|                          | Microbleed present**        | 0.507    | 0.164| 89  | 3.09    | 0.0027  |
|                          | EYO                         | -0.012   | 0.012| 89  | -1.08   | 0.2833  |
|                          | EYO* Mutation               | 0.028    | 0.012| 89  | 2.3     | 0.0236  |
|                          | AGE                         | 0.002    | 0.009| 89  | 0.27    | 0.785   |
|                          | APOE-ε4, Positive           | 0.02     | 0.124| 89  | 0.16    | 0.8707  |

*p<0.05;  
** p<0.01;  
***p<0.001

https://doi.org/10.1371/journal.pone.0195838.t002
Finally, when we limited analyses to those individuals with microbleeds (n = 26) and tested whether the number of microbleeds mediated the relationship between mutation status and regional or global WMH volume, we did not find evidence of a mediational relationship (p’s > 0.63).

Discussion

Several important observations emerged from this work among individuals with and without genetic mutations for AD. First, the primary aim of this study was to determine the extent to which the increased WMH among mutation carriers reflects, or is mediated by, increases in vascular forms of beta amyloid, which we operationally defined as presence of cerebral microbleeds. Although we observed some co-dependency between WMH and cerebral microbleeds, the increased WMH volume among mutation carriers was only modestly mediated by this marker of cerebral amyloid angiopathy. Second, those with microbleeds had more severe AD fluid biomarker profiles, defined as lower levels of CSF Aβ42 and lower CSF Aβ42/tau ratios. Third, individuals with mutations were more likely to have cerebral microbleeds than those without mutations, although this increased likelihood did not vary as a function of estimated time to symptom onset, perhaps due to a relatively small sample size (S4 Table). Finally, we were able to reproduce our previous finding[2] of increased WMH volume among mutation
carriers up to 20 years prior to expected symptom onset in this subset of participants with available GRE scans.

There is considerable debate about the role of cerebrovascular disease in AD onset and pathogenesis. Current pathogenic models of the disease[16] and their application to clinical diagnostic criteria[17–19] emphasize a single pathway that begins with fibrillar forms of (parenchymal) beta amyloid, followed by the deposition of tau pathology, which subsequently results in neurodegeneration and clinical symptoms. But there is ample evidence of involvement of cerebrovascular disease in AD. Postmortem studies consistently demonstrate that the presence of cerebrovascular lesions among symptomatic individuals with AD is much more common than not and suggest that pathologies, including cerebrovascular disease, in addition to primary AD pathology, lower the threshold, increase risk, or are perhaps necessary for the disease to express clinically[20]. In vivo neuroimaging studies support a similar conclusion: up to one third of older adults with no apparent symptomatology have evidence of amyloid deposition sufficient enough to meet pathological criteria for AD[21], but increased markers of cerebrovascular disease seem to distinguish symptomatic individuals with amyloidosis from asymptomatic individuals with amyloidosis[22]. A common interpretation of such findings is that cerebrovascular disease represents a comorbidity that lowers the clinical diagnostic threshold for AD and contributes additively to disease presentation. The opportunity to test the extent to which cerebrovascular disease is playing a role among individuals with autosomal dominant genetic mutations for AD offers the unique opportunity to test the extent to which cerebrovascular disease is a “core” feature of AD; the work here, combined with our previous observation[2], provides evidence that WMH are not merely a comorbidity or confounding factor but rather reflect primary pathological features of the disease, present in individuals genetically-determined to develop the disease. Participants in this study were all of equal likelihood of inheriting an autosomal dominant mutation for AD and were essentially “randomly

|                      | Effect | Estimate | S.E. | 95% CI     | z      | p-value |
|----------------------|--------|----------|------|------------|--------|---------|
| **Total WMHI Volume**|        |          |      |            |        |         |
| total                |        | 0.3896   | 0.1172| 0.1634     | 0.6304 |    3.3248| 0.0009 |
| direct               | **     | 0.3126   | 0.1116| 0.0894     | 0.5256 |    2.8011| 0.0051 |
| indirect             |        | 0.077    | 0.0521| -0.0057    | 0.1974 |    1.4797| 0.1389 |
|                      |        |          |      |            |        |         |
| **Frontal Lobe**     |        |          |      |            |        |         |
| total                |        | 0.1069   | 0.0484| 0.0113     | 0.2092 |    2.2075| 0.0273 |
| direct               |        | 0.0774   | 0.043 | -0.0048    | 0.1654 |    1.7998| 0.0719 |
| indirect             |        | 0.0295   | 0.0243| -0.0056    | 0.0842 |    1.214 | 0.2247 |
|                      |        |          |      |            |        |         |
| **Temporal Lobe**    |        |          |      |            |        |         |
| total                | **     | 0.1067   | 0.0405| 0.038     | 0.1963 |    2.6351| 0.0084 |
| direct               |        | 0.0746   | 0.0321| 0.0199     | 0.1487 |    2.3238| 0.0201 |
| indirect             |        | 0.032    | 0.0238| -0.0032    | 0.0867 |    1.3486| 0.1775 |
|                      |        |          |      |            |        |         |
| **Parietal Lobe**    |        |          |      |            |        |         |
| total                | **     | 0.2207   | 0.074 | 0.0937     | 0.3846 |    2.9843| 0.0028 |
| direct               | **     | 0.158    | 0.0562| 0.064     | 0.2833 |    2.8118| 0.0049 |
| indirect             |        | 0.0628   | 0.044 | -0.0045    | 0.163  |    1.4259| 0.1539 |
|                      |        |          |      |            |        |         |
| **Occipital Lobe**   |        |          |      |            |        |         |
| total                | ***    | 0.2378   | 0.0643| 0.12      | 0.3801 |    3.6973| 0.0002 |
| direct               | **     | 0.1965   | 0.0606| 0.0871     | 0.3248 |    3.2438| 0.0012 |
| indirect             |        | 0.0413   | 0.0265| -0.0013    | 0.1051 |    1.5599| 0.1188 |

*p<0.05; **p<0.01; ***p<0.001;

All models were adjusted for APOE -4 and age.

https://doi.org/10.1371/journal.pone.0195838.t003

White matter hyperintensities and amyloid angiopathy

PLOS ONE | https://doi.org/10.1371/journal.pone.0195838 May 9, 2018 10 / 15
assigned” to the carrier or non-carrier groups, thus providing experimental evidence for increased WMH in genetically-determined AD.

White matter hyperintensities are typically considered markers of small vessel cerebrovascular disease and postmortem correlates studies suggest several changes secondary to ischemic injury, including demyelination, axonal loss, blood barrier dysfunction, and arteriolosclerosis [3]. Because of the high levels of amyloidosis among individuals with autosomal mutations for AD[1], the extent to which WMH reflects CAA is a possibility that motivated the current study. There is understandably little information about pathological changes in the white matter of individuals with autosomal dominant forms of AD, considering the low prevalence of individuals with autosomal forms of AD. In one study, WMH volume determined in vivo

| Effect | Estimate | S.E. | 95% CI | z    | p-value |
|--------|----------|------|--------|------|---------|
| Total WMH volume | EYO‘Mutation | 0.0313 | 0.0105 | 0.0113 0.0526 | 2.9924 | 0.0028 |
| direct | Mutation | 0.5541 | 0.1438 | 0.2862 0.8461 | 3.8529 | 0.0001 |
| indirect | EYO‘Mutation | 0.0033 | 0.0036 | -0.0024 0.0117 | 0.9217 | 0.3567 |
| Frontal Lobe | EYO‘Mutation | 0.0105 | 0.0054 | -0.0003 0.0211 | 1.9463 | 0.0516 |
| direct | Mutation | 0.1615 | 0.0625 | 0.0321 0.289 | 2.5852 | 0.0097 |
| indirect | EYO‘Mutation | 0.0012 | 0.0018 | -0.0016 0.006 | 0.6843 | 0.4938 |
| Temporal Lobe | EYO‘Mutation | 0.0089 | 0.0036 | 0.0024 0.0172 | 2.4608 | 0.0139 |
| direct | Mutation | 0.1546 | 0.0532 | 0.0667 0.2708 | 2.9074 | 0.0036 |
| indirect | EYO‘Mutation | 0.0014 | 0.0019 | -0.0016 0.0055 | 0.74 | 0.4593 |
| Parietal Lobe | EYO‘Mutation | 0.0132 | 0.0061 | 0.0022 0.0261 | 2.1683 | 0.0301 |
| direct | Mutation | 0.291 | 0.0957 | 0.1232 0.4993 | 3.0459 | 0.0024 |
| indirect | EYO‘Mutation | 0.0035 | 0.0033 | -0.0022 0.0114 | 1.0586 | 0.2898 |
| Occipital Lobe | EYO‘Mutation | 0.0132 | 0.0055 | 0.0027 0.0239 | 2.4168 | 0.0157 |
| direct | Mutation | 0.308 | 0.0757 | 0.1683 0.4728 | 4.0668 | <0.0001 |
| indirect | EYO‘Mutation | 0.0019 | 0.0018 | -0.0008 0.0062 | 0.4018 | 0.3069 |

*p<0.05; **p<0.01; ***p<0.001;
All models were adjusted for APOE-4 and age.

https://doi.org/10.1371/journal.pone.0195838.t004
correlate modestly with CAA restricted to the temporal lobes, but also correlated with leptomeningeal blood vessel diameter and lower density of CD68-positive microglia in posterior brain regions, where the impact of WMH is greatest[2, 4]. The findings here also suggest that the increased observed WMH in autosomal dominant AD is not attributable entirely to CAA. It is important to note that among autosomal dominant mutation carriers for AD, the pathophysiological basis of WMH has not been elucidated clearly, and could include damage due to ischemia, as is observed in aging, or to other factors such as blood brain barrier dysfunction, Wallerian-like degeneration secondary to neurodegeneration, and inflammation. Thus, we speculate that the role of WMH in autosomal dominant AD reflects either the primary involvement of vascular damage in AD or the manifestation of other pernicious factors, such as inflammation, in AD. Indeed, a recent study showed some preliminary evidence of increased T-lymphocytic responses in the postmortem white matter tissue of PSEN1 mutation carriers [23]. Nonetheless, our results suggest that both radiological phenomena—microbleeds and WMH—are important features of AD. Future work should therefore consider more explicitly the underlying mechanisms as potential drivers of disease pathogenesis and treatment targets as opposed to comorbidities not central to the disease.

Cerebral microbleeds in the current study were measured on GRE 3T MRI scans. These scans are known to have good specificity for microbleed detection but relatively lower sensitivity compared with susceptibility weighted images and higher field strength magnets. Relatively few microbleeds were detected and it is possible that some participants had microbleeds that were undetected by the technology employed, thus somewhat biasing our analyses towards the null hypothesis and producing Type II statistical errors. On the other hand, the high specificity of microbleed detection on GRE gives us confidence that individuals identified as having microbleeds were accurately classified and have evidence of the presence of CAA. When we restricted the sample to only those participants with detectable microbleeds, we also did not find a mediating role of CAA in the relationship between mutation status and WMH volume, which supports our overall observation, although relatively low sample size could also bias the findings somewhat towards the null. Furthermore, microbleeds that distributed in subcortical/deep regions are typically attributed to hypertensive pathology whereas microbleeds distributed in lobar regions are typically attributed to CAA. Not surprising for the age and population under study, microbleeds in the current sample tended to be in lobar regions. Only two participants had exclusively deep microbleeds. We re-ran the analyses coding these individuals as having microbleed status of “absent” and the results remained essentially unchanged (data not shown).

The development of disease modifying interventions for AD has resulted in a number of disappointing results[24]. Recent trials that focused on treatments that attempt to clear fibrillar amyloid pathology or prevent its deposition yielded negative findings with respect to clinical outcomes and removal of amyloid, despite some moderate evidence of target engagement[24]. There has been little focus on vascular mechanisms as feasible targets for treatment of prevention strategies. This work adds to a growing body of literature that clearly implicates WMH in AD; future work should consider mechanisms of WMH including cerebrovascular disease and interventions that focus on cerebrovascular disease in AD.

Supporting information

S1 Table. Distribution of microbleed status by age group. There was a trend of increasing microbleeds as the EYO increases (chi-square test p-value: 0.08). However, after adjusting for family, age at visit, and E4, there was no significant increasing trend.

(DOCX)
S2 Table. Mediation and moderated mediation results with CDR-SB as a covariate (n = 175). In addition to CDR-SB, age, EYO and ApoE-4 was controlled. (DOCX)

S3 Table. Mediation and moderated mediation results for the subset of CDR-SB≤.5 (n = 134). In the models, age, EYO and ApoE-4 was controlled. (DOCX)

S4 Table. Mediation and moderated mediation results without APP subtype (n = 138). In the models, age, EYO and ApoE-4 was controlled. (DOCX)

Acknowledgments

S.L. is supported by NIH/NIA AG051348. Data collection and sharing for this project was supported by The Dominantly Inherited Alzheimer’s Network (DIAN, UF1AG032438) funded by the National Institute on Aging (NIA), the German Center for Neurodegenerative Diseases (DZNE), Raul Carrea Institute for Neurological Research (FLENI), Partial support by the Research and Development Grants for Dementia from Japan Agency for Medical Research and Development, AMED, and the Korea Health Technology R&D Project through the Korea Health Industry Development Institute (KHIDI). This manuscript has been reviewed by DIAN Study investigators for scientific content and consistency of data interpretation with previous DIAN Study publications. We acknowledge the altruism of the participants and their families and contributions of the DIAN research and support staff at each of the participating sites for their contributions to this study.

A description of the Dominantly Inherited Alzheimer Network observational study related entities can be found at https://dian.wustl.edu/our-research/observational-study/dian-observational-study-related-entities/

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