**Background** Two markers of cerebral small vessel disease are white matter hyperintensities and cerebral microbleeds, which commonly occur in people with Alzheimer’s disease.

**Aim and/or hypothesis** To test for independent associations between two Alzheimer’s disease-susceptibility gene loci – APOE ε and the TOMM40 ‘523’ poly-T repeat – and white matter hyperintensities/cerebral microbleed burden in community-dwelling older adults.

**Methods** Participants in the Lothian Birth Cohort 1936 underwent genotyping for APOE ε and TOMM40 523, and detailed structural brain magnetic resonance imaging at a mean age of 72.70 years (standard deviation = 0.7; range = 71–74).

**Results** No significant effects of APOE ε or TOMM40 523 genotypes on white matter hyperintensities or cerebral microbleed burden were found amongst 624 participants.

**Conclusions** Lack of association between two Alzheimer’s disease susceptibility gene loci and markers of cerebral small vessel disease may reflect the relative health of this population compared with those in other studies in the literature.

Key words: brain microbleeds, epidemiology, MRI, neurology, risk factors, vascular events

**Introduction**

There is evidence that the presence of cardiovascular disease pathology can increase the future risk of Alzheimer’s disease (AD) and cognitive decline (1). White matter hyperintensities (WMH) and cerebral microbleeds (CMB) are generally considered to reflect cerebrovascular burden in ageing. They are manifestations and markers of cerebral small-vessel disease and often co-occur (2).

The mechanisms underlying significant association between cardiovascular and neurodegenerative pathology are unclear; however, there are three main hypotheses (1). Firstly, it is possible that cardiovascular diseases and AD/cognitive decline share common risk factors and are not mechanistically related (1). Secondly, it is possible that cardiovascular burden may expedite progression of AD/cognitive decline through promoting atherosclerosis and accumulations of amyloid-beta plaques, and/or (thirdly) by increasing vulnerability to such pathology and lowering the threshold at which cognitive decline becomes apparent behaviorally, even in the absence of a mechanistic link (1,3).

Two genetic risk factors for AD and age-related cognitive decline are in the APOE ε and TOMM40 gene loci (4). Two recent meta-analyses reported no overall significant association between APOE ε4 and WMH in older adults (P > 0.05). Paternoster et al. (5) did not stratify analyses by whether participants were generally healthy or not (total n = 8546), whereas Schilling et al. (6) did (‘healthy’ n = 8405). However, these reports were not independent because some common data were included in both. In contrast, two meta-analyses reported a significant association between APOE ε4 and CMB: Schilling et al. (6) (‘healthy’ n = 5387; P = 0.002) and Maxwell et al. (7) (total n = 7351; P < 0.001). These two reports also had a degree of overlapping datasets. A more recent individual study (8) reported similar results (n = 1965, P < 0.05).

In the above reports, the positive association between APOE ε4 and CMB burden was not completely consistent; other genetic predictor variables may exert independent effects. The TOMM40 rs10524523 (‘523’) variable length poly-T repeat has been significantly associated with brain phenotypes such as cognitive decline,
independent of APOE genotype (9). The TOMM40 523 locus is characterized by a variable number of T residues (poly-T repeats) that can be grouped into ‘short’ (<20; ‘S’), ‘long’ (20–29; ‘L’), and ‘very long’ (≥30; ‘VL’) (10). Roses (11) plotted histograms showing the distributions of poly-T repeat lengths in different APOE genotypes: ε3/ε3, ε3/ε4, and ε4/ε4. The poly-T repeat was strongly linked with the APOE ε haplotype; ε4 is linked to L, with ε3 linked to either S or VL alleles (4); investigating the effects of TOMM40 523 genotype on brain-related phenotypes may explain some of the heterogeneity in the possible APOE ε4 and WMH/CMB association. This study therefore aims to contribute a large amount of relevant genetic APOE/TOMM40 and WMH/CMB brain imaging data, from a sample of community-dwelling older adults.

Methods
Sample and genotyping
The Lothian Birth Cohort 1936 (LBC1936) is a longitudinal sample of generally healthy community-dwelling older adults (12). All participants were born in 1936, and most resided in the Edinburgh area of Scotland in older age. The sample received detailed cognitive, medical, and demographic assessments at the Wellcome Trust Clinical Research Facility (Edinburgh; http://www.wtrcf.ed.ac.uk) at age ~73 years. Participants underwent detailed brain MRI around the same time (13) (mean interval = 65±0 days, SD = 39±5). Of the 866 LBC1936 participants that attended clinic assessment, 700 completed neuroimaging (mean age = 72±70, SD = 0±7). Details of LBC1936 recruitment and assessment, including aspects of possible selection bias and attrition, can be found in two cohort protocol papers by Deary et al. (12,14).

Participants were genotyped by TaqMan assay for APOE ε (Applied Biosystems, Carlsbad, CA, USA) using DNA isolated from whole blood (12). TOMM40 523 was genotyped by the laboratory of Dr. Ornit Chiba-Falek (Duke University) as described previously (15).

Brain MRI
Participants underwent whole brain structural MRI, acquired using a GE Signa Horizon 1·5 T HDxt clinical scanner (General Electric, Milwaukee, WI, USA) equipped with a self-shielding gradient set (33 mT/m maximum gradient strength) and manufacturer-supplied eight-channel phased-array head coil, lasting around 70 min. In addition to standard structural T2-, T2*- weighted, and FLAIR-weighted MRI, the imaging protocol included a high-resolution T1-weighted volume sequence acquired in the coronal plane with field-of-view of 256×256 mm, imaging matrix 192×192 (zero-filled to 256×256), 160 1·3-mm thick slices giving 1×1×1·3-mm voxel dimensions (13). The repetition, echo, and inversion times were 10, 4, and 500 ms respectively. The detailed protocol for WMH/CMB image processing, and intracranial/total brain volume measurement, is published by Wardlaw et al. (13). WMH volumes were calculated from binary masks generated by an in-house-developed and validated software tool written in MATLAB that applies a technique named Multispectral Colouring Modulation and Variance Identification:
There were no significant associations between APOE ε4 presence (vs. absence), or TOMM40 523 genotype (in any analyses), and WMH/CMB variables (all $P > 0.05$; Tables S2–S3).

Discussion

Our findings align with previous meta-analyses in observing no significant APOE/WMH association (5,6). In terms of CMB, this report does not align with recent meta-analyses that concluded significant deleterious effects of APOE ε4 (6,7). Of those meta-analyses, Schilling et al. (6) observed a significant effect of APOE ε4 in general populations only – and not in pooled samples with neurological or vascular disorders; the lack of association in LBC1936 may be because of the relatively good health of the sample. Our findings do align with two individual studies of generally healthy older adults (included in the meta-analyses) which reported no significant APOE ε4 present (vs. absent) effects [by Sveinbjörnsdóttir et al. (21) ($n = 1725$) and Jeerakkathil et al. (22) ($n = 368$)]. There was no evidence of an independent effect of TOMM40 523 genotype here.

Previous significant associations in individual CMB reports may perhaps reflect a degree of type 1 error, particularly in smaller samples. Several studies report broader age ranges than examined here (71–74 years; SD = 0.7) (7). Any effect of age on CMB may be via processes associated with age; controlling for age statistically is unlikely to completely eradicate these effects (23), so wide age ranges could possibly contribute to spurious genetic associations.

The BOMBS instrument allows raters to note CMBs as either definite or possible [a cautious category to avoid misclassifications of mimics (17)]. It would be interesting to examine if previously reported significant APOE-CMB associations are affected when analyzed to incorporate possible microbleeds/mimics.

It is possible that the sample size examined here is not sufficiently powered to detect any possibly modest effects of APOE or TOMM40 genotypes on WMH/CMB (5). It is possible that the LBC1936 sample is generally healthier when compared with other samples, exacerbated by a selection bias where healthier participants were more likely to attend brain MRI assessment (24). Generally, the LBC1936 sample is slightly restricted in range towards the upper end of general mental ability and socioeconomic status (14). In addition, APOE ε4 genotype has previously been associated with earlier mortality and cardiovascular disease (25); it is possible that a selection bias exists whereby healthier participants are more likely to attend cognitive or brain imaging assessment, and this may contribute to our finding no effect of APOE/TOMM40 genotypes on WMH/CMB phenotypes with MRI.

Maxwell et al. (7) estimated with a ‘fail-safe N calculation’ that null studies including at least 7700 participants would be required to attenuate their meta-analysis APOE ε4/CMB association (reported $P = 0.01$) to non-significance (i.e. $P > 0.05$). Further independent studies will help to define the more exact nature and strength of any APOE/CMB association in generally healthy populations.

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Authors’ contributions

Designed the experiments: D. M. L., J. M. W., D. J. P., I. J. D. Analyzed the data/wrote the manuscript: D. M. L. Interpreted the results, critically revised content, and approved the final version: All authors.

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Supporting Information
Additional Supporting Information may be found in the online version of this article at the publisher’s web-site:

Table S1. Frequency statistics for APOE/TOMM40 poly-T repeat genotypes.

Table S2. APOE/TOMM40 genotypes and white matter hyperintensities/cerebral microbleeds: association statistics.

Table S3. TOMM40 genotypes and white matter hyperintensities/cerebral microbleeds in APOE subgroups: association statistics.