**Abstract**

APOE plays a well-established role in lipid metabolism. Animal model evidence suggests APOE may also be associated with adiposity, but this has not been thoroughly investigated in humans. We measured adiposity (BMI, truncal fat mass, waist circumference), physical activity (PA), cardiorespiratory fitness and APOE genotype (E2, E3, E4) in 292 8-year-old children from the Tasmanian Infant Health Survey (TIHS), an Australian population-based prospective birth cohort. Our aims were to examine the association of APOE with child adiposity, and to examine the interplay between this association and other measured factors. We found that APOE was associated with child lipid profiles. APOE was also associated with child adiposity measures. The association was E4 allele-specific, with adiposity lower in the E4-containing group (BMI: Mean difference -0.90 kg/m²; 95% confidence intervals (CI) -1.51, -0.28; p = 0.004). The association of APOE4 with lower BMI differed by fitness status (difference in effect p = 0.002), and was more evident among the less fit (Mean difference -1.78 kg/m²; 95% CI -2.74, -0.83; p<0.001). Additionally, associations between BMI and lipids were only apparent in those of lower fitness who did not carry APOE4. Similar overall findings were observed when truncal fat mass and waist circumference were used as alternative adiposity measures. APOE4 and cardiorespiratory fitness could interact to influence child adiposity. In studies addressing the genetic determinants of childhood obesity, the context of child fitness should also be taken into account.

**Introduction**

The plasma protein apolipoprotein E (apoE), encoded by the gene APOE, plays an important role in lipid metabolism. ApoE carries lipids in the bloodstream, and mediates the influx of lipids into cells such as adipocytes [1]. There are three isoforms; e2, e3 and e4, encoded by three alleles, E2, E3, and E4. The isoforms differ in their binding affinities for lipids and lipoprotein receptors [2].

There is a well-established relationship between serum LDL cholesterol (LDL-C) and genotypes of APOE in adults and in children. The relationship is approximately linear, with E2 associated with the lowest, and E4 associated with the highest, LDL-C, as demonstrated by Bennet and colleagues by meta-analysis [2]. For children specifically, equivalent relationships between APOE genotype and LDL-C have also been repeatedly demonstrated [3,4,5,6,7].

The determination of body mass index (BMI) and the development of obesity are thought to be controlled, at least in part, by the regulation of lipid flux by adipose tissue [1]. Adipose tissue serves as a storage site for triglycerides (TGs) derived from lipoproteins delivered by the circulation. ApoE is highly expressed in adipocytes, and rodent apoE knockouts (EKO) show smaller adipocytes containing significantly less TG compared to wildtype. Whilst circulating apoE has been shown to also play a role, transplantation of EKO adipocytes into wildtype animals has demonstrated the importance of endogenous apoE in determining adipocyte size and TG content [1,8].

There is evidence to suggest that the ability to store TGs may differ between human apoE isoforms. When fed a ‘Western-style’ high-fat diet for eight weeks, knock-in mice containing human APOE3 gained 30% more weight than APOE4 knock-ins [9]. Thus, human APOE genotype may be important in determining adiposity. One adult study investigating APOE with lipids and coronary risk suggested that there may be an association between APOE genotype and BMI, with E4 carriers having a (non-significantly) lower BMI than E3/E3 or E2 carriers in both whites and African
Americans [10]. However, recent large scale genome-wide association analyses [11] have not detected an association of APOE genotype with human adiposity. Little data has been available for children, however, it might be argued that child studies may provide a clearer picture due to a lack of confounding by co-morbidities and resultant medication.

Further, effect modification of the APOE-BMI association will be important to consider. A recent study examining interaction between obesity-associated genes and physical activity in European adults indicated that genetic predisposition to obesity is significantly attenuated by a physically active lifestyle [12]. Studies including the Cardiovascular Risk in Young Finns Study have demonstrated that physical activity (PA) appears to act as an effect modifier on the relationship between APOE genotype and serum lipids [7,13]. Thus, given that PA, and also cardiorespiratory fitness (CRF), have obvious effects on energy balance, we hypothesised that PA and/or CRF might also modify any effect of APOE on adiposity. We therefore explored the relationship between APOE genotype, lipids, PA, CRF, and measures of adiposity, using relevant data available from participants of the Tasmanian Infant Health Survey (TIHS), a prospective birth cohort study.

Materials and Methods

Ethics Statement

The Human Research Ethics Committee (University of Tasmania) approved each stage of the study. Parental written consent and child verbal assent was obtained.

Study sample

Singleton participants in the THIS born in 1989 who had participated in a follow-up study in Southern Tasmania at age 7–8 years [14,15] and were still residing in the South of the State (a defined geographical region based on telephone code) in 2002, were eligible for this study.

During the years 1988-1995, 10,562 newly-born infants were recruited into the THIS, which had been established to investigate sudden infant death syndrome (SIDS) [16]. The selection of eligible singleton subjects was based on SIDS risk factors as described previously [17]. Parents of 1182 of the surviving infants among 1256 eligible singletons who were born specifically in 1989 participated in an in-hospital interview. In 1997, 530 of these children (now 8 years of age) who were deemed eligible for a cholesterol study were identified at schools in southern Tasmania and invited to participate; 338 did so. Detailed anthropometric measures and fasting blood samples for lipid analysis and measures of glucose and insulin were collected [14,15]. In 2002, 333 of these were traced to an address in southern Tasmania and 339 agreed to participate in a further study investigating genetic factors. Of these, 292 previously had skin folds and serum insulin measured at 8 years of age in 1997, and these children formed the sample for this and previous gene-environment studies [16].

Measurements

Children underwent measurements of anthropometry and had a fasting blood sample taken. Weight was measured in light clothing using scales that were calibrated daily. Height was measured in bare feet using a stadiometer. BMI was calculated as the ratio of weight to squared height. Waist circumference was measured. Skin-fold thickness was measured with callipers at the mid-abdominal, subcapular, and suprailliac sites, with triplicate measures taken at each site and averaged. Truncal fat mass was calculated as the mean skin-fold thickness from these three sites.

Blood samples were analysed by a laboratory accredited by National Association of Testing Authorities and participating in Royal College of Pathologists of Australasia/Australasian Association of Clinical Biochemists external quality assurance programmes. The Vitros analyser was used for biochemical estimation of serum TG (Ortho Clinical Diagnostics). Child physical activity (PA) was measured by pedometer over one school lunchtime. The number of recorded steps was adjusted for the length of time the pedometer was worn. PA was also recorded via parent-reported usual activity during lunchtime [15]. Reported activities were categorised into low/moderate (sit/talk, read/study, walk, use play equipment) or high (run, sports training) activity levels for the purposes of analysis. Child CRF was assessed by the 20 metre endurance multistage shuttle run test. This test required children to run back and forth between two lines set 20 m apart with a protocol of increasing velocity and scoring by laps completed at various shuttle run velocity levels [19]. This test has been validated as a measure of aerobic fitness in children [20].

DNA collection, extraction and genotyping

Buccal mucosa swabs were collected with Gentra PureGene brushes and DNA extracted using PureGene DNA Isolation Kits (Gentra Systems, MN, USA). The two nucleotide substitutions, a C to T at codon 112 (Cys112Arg, rs429358) and a C to T at codon 158 (Cys158Arg, rs7412) in APOE that encode the E2, E3 and E4 alleles were detected as described previously [18].

Data analysis

Data were described using means and standard deviations or medians and inter-quartile ranges. The distribution of TG was right skewed and was log-transformed prior to analysis. Characteristics of the participants were compared between APOE groups using analysis of variance and chi-squared tests.

Consistent with a number of previous studies [2], APOE genotypes were grouped into three categories according to E2 and E4 carrier status: E2 carriers (E2/E2, E2/E3), E4 carriers (E4/E4, E4/E3), and reference (E3/E3). Individuals carrying E2/E4 (n = 7) were excluded from this classification. We then dichotomised the APOE genotypes in two ways: E4-containing (E3/E4, E4/E4) versus not E4-containing (E2/E2, E2/E3, E3/E3), and E2-containing (E2/E2, E2/E3) versus not E2-containing (E4/E4, E4/E3, E3/E3) groups.

The association between BMI and APOE was investigated using linear regression models adjusted for age and sex. Estimated differences in mean BMI with 95% confidence intervals and Wald test p-values are presented. Confounders of the association between BMI and APOE were identified on the basis of whether the estimated association changed by more than 10% when the confounder was entered into the model. Linear regression models of BMI on APOE further adjusted for lipids and insulin were fitted to separate direct effects of APOE on BMI from those potentially mediated through the lipids or insulin. Finally, sex, PA and CRF were each considered as potential modifiers of the association between BMI and APOE. Each potential modifier was added singly to the regression model with a product term representing the interaction between APOE and the potential modifier. PA and CRF were initially included as continuous variables, then dichotomised at the median.

The association between lipids and APOE was investigated using linear regression models adjusted for age and sex. CRF was considered as a potential modifier of this association, so was added
to the model with an interaction term between dichotomised fitness and APOE.

Finally, a linear regression model of BMI on lipids was fitted within categories defined by dichotomised CRF (high fit; at or above median, vs low fit; below median) and APOE genotype (E4-containing vs not E4-containing), adjusted for age and sex.

P-values presented are two-sided. A p-value less than 0.05 was considered significant. All data analyses were performed in Stata Version 10.1 (Statacorp).

Results

APOE genotype is associated with lipid profile in the TIHS

The sample consisted of 292 children (208 boys, 84 girls) with a mean age of 8.2 years. A total of 290 children (99.3%) were successfully genotyped for the APOE variants. The genotype frequencies for the two SNPs were as follows: rs429358 TT 71.7% (206/290), TC 25.9% (75/290), CC 2.4% (7/290); rs7412 TT 1.0% (3/290), TC 14.8% (43/290), TT 84.1% (244/290). Both variants were in Hardy Weinberg Equilibrium (rs429358: p = 0.99; rs7412: p = 0.78). Initially, APOE genotypes were grouped into three categories according to E2 and E4 carrier status: E2 carriers (n = 39), E4 carriers (n = 75), and E3/E3 reference (n = 169). Table 1 shows characteristics of the study sample by APOE genotype. As expected, we found strong evidence that APOE genotype was associated with LDL-C (p<0.001), and to a lesser extent with HDL/Total cholesterol ratio (HDL/Total-C) and log-transformed triglyceride (TG) levels. Additionally, APOE genotype was associated with a number of adiposity measures, including BMI (p = 0.01), skinfold measures (eg suprailiac, p = 0.03), and waist circumference (p = 0.02). No associations were detected between APOE genotype and CRF or PA.

APOE4, but not APOE2 is associated with adiposity

Table 2 shows the characteristics of participants after dichotomising into E4-containing (n = 75) and not E4-containing (n = 215) genotype groups. Of the lipid measures, only higher LDL-C was associated with E4-containing genotype (p = 0.03). However, E4 was shown to be associated with reduced adiposity (eg E4-containing: lower BMI, p = 0.004; reduced truncal fat mass, p = 0.02; lower waist circumference, p = 0.006).

When participants were dichotomised into E2-containing (n = 39) and not E2-containing (n = 244) genotype groups, E2 dichotomised APOE genotype was associated with measures of lipids (E2-containing: lower LDL-C, p<0.001; higher HDL/Total-C ratio, p<0.001; higher HDL-C, p = 0.02; higher TG, p = 0.01), but there was no evidence of association of APOE2 with adiposity.

APOE4 remains associated with BMI after adjustment for confounders

The evidence of association between APOE4 and lower BMI was of particular interest. To further explore this, we considered the involvement of possible confounders. First, adjustment for age and sex did not alter the association (Mean difference = 0.87 kg/m²; 95% CI 0.26, 1.47; p = 0.006). A number of other variables in the dataset that were potentially related to BMI were also considered as confounders, including birth weight, length and head circumference, maternal age, alcohol consumption by the mother in pregnancy, and also CRF and lower PA in childhood. None materially changed the association when added into the model individually.

An investigation of whether lipids and insulin may be on the causal pathway from APOE4 genotype to BMI

We tested the hypothesis that the association of APOE4 with BMI may be party mediated by the relationship between APOE4 and LDL-C. We found that the magnitude of the association between APOE4 and BMI was not reduced when adjusted for LDL-C (Mean difference = 0.99 kg/m²; 95% CI 0.38, 1.61; p = 0.002). APOE4 was also associated with insulin (p = 0.027); adjustment of the APOE4 - BMI association by insulin reduced, but did not remove, the relationship (Mean difference = 0.75 kg/m²; 95% CI 0.15, 1.36; p = 0.015). Similar adjustments for other lipids and glucose also did not alter the association. Therefore, the association between APOE4 genotype and lower child BMI appeared independent of measured metabolic profile.

Physical activity and fitness are associated, but only fitness is associated with lipids

PA and CRF were found to be moderately associated. For example, children with a higher lunchtime pedometer score were more likely to complete extra laps of the shuttle test (p = 0.011). No associations were seen between PA (pedometer or parent-report) and lipids (adjusted for age and sex). However, higher fitness was associated with higher HDL-C (p = 0.004), higher HDL/Total-C ratio (p = 0.034), and lower TG (p = 0.026) (adjusted for age and sex). Therefore fitness appeared more relevant to lipid profile than PA in this study.

Fitness appears to modify the relationship between APOE4 and BMI

We considered three possible effect modifiers of the APOE4 – lower BMI association; sex, PA, and CRF. No interactions were detected for sex (adjusted for age), or for either PA measure (adjusted for age and sex). However, a significant interaction was identified between APOE4 and CRF (adjusted for age and sex) in relation to BMI. When assessed as a continuous variable, lower fitness potentiated the influence of APOE4 on BMI (difference in effect (significance of interaction term) p = 0.022). When CRF was dichotomised at the median, it was found that the association between APOE4 and lower BMI was strong in those of low fitness (n = 142) (Mean difference = -1.78 kg/m²; 95% CI -2.74, -0.83; p<0.001), but was absent in those of high fitness (n = 148) (Mean difference = 0.074 kg/m²; 95% CI 0.15, 0.73; p = 0.03) (difference in effect p = 0.002) (Table 3).

Neither PA nor fitness appears to modify APOE4 - lipid associations

The association between APOE4 and higher TG was stronger among those with high parent-reported PA (difference in effect p = 0.030, adjusted for age and sex). Fitness status did not modify the association between APOE4 (adjusted for age and sex) and Total-C (difference in effect p = 0.84), LDL-C (p = 0.64), HDL-C (p = 0.58), HDL/Total-C ratio (p = 0.49), or TG (p = 0.30).

Association between BMI and lipids is determined by fitness and APOE4 genotype

We also examined the associations between BMI and lipids. Both HDL/total-C ratio (p = 0.028) and TG (p<0.001) were significantly associated with BMI overall. When CRF was considered as an effect modifier, it was demonstrated that these associations were only present in those of lower CRF (adjusted for age and sex) (BMI and HDL/total-C ratio p = 0.022; difference in effect p = 0.034; TG p = 0.001; difference in effect p = 0.038). This suggests that the apparent lack of effect of APOE4 on BMI that is
evident in children with higher fitness may be related to an uncoupling of the relationship between BMI and blood lipids and with greater fitness.

Further, when the fitness groups were then dichotomised by presence or absence of APOE4, it was found that significant associations between BMI and lipids were only evident in those who were non-E4 and lower fitness (Table 4). It is in this same group that BMI is significantly elevated when compared to all other fitness/APOE4 combinations (Table 3). Thus, presence of an APOE4 allele appears to provide protection from increased BMI in children of low CRF, by removing the BMI-lipid association similarly to that found in children of higher fitness (and lower BMI). In contrast, low-fit non-E4 children tended to have higher BMI, and a strong relationship between BMI and lipid levels, especially a positive relationship between BMI and TGs.

**Table 1.** Characteristics of the participants by ApoE genotype.

|                  | E3/E3 (n = 169) | E2 containing (n = 39) | E4 containing (n = 75) | p-value† |
|------------------|-----------------|------------------------|------------------------|----------|
|                  | Mean            | SD                     | Mean                   | SD       |
| Child age        | 8.20            | 0.31                   | 8.15                   | 0.35     | 8.14                | 0.31                   | 0.27                 |
| Male             | 73.37% (124/169) | 58.97% (23/39)         | 58.87% (54/75)         | 0.20     |
| Serum Total Cholesterol (mmol/l) | 4.32 | 0.70                   | 4.11                   | 0.64     | 4.45                | 0.70                   | 0.05                 |
| Serum LDL-cholesterol (mmol/l) | 2.63 | 0.64                   | 2.26                   | 0.50     | 2.75                | 0.66                   | <0.001               |
| Serum HDL-cholesterol (mmol/l) | 1.53 | 0.33                   | 1.66                   | 0.36     | 1.53                | 0.32                   | 0.07                 |
| Serum HDL/total cholesterol ratio | 0.36 | 0.08                   | 0.41                   | 0.08     | 0.35                | 0.08                   | 0.001                |
| Serum triglycerides (mmol/l)* | 0.66 | 0.56, 0.87              | 0.81                   | 0.64, 1.06 | 0.76               | 0.60, 0.97              | 0.01                 |
| Birthweight (kg) | 3.17            | 0.80                   | 3.14                   | 0.76     | 3.05                | 0.80                   | 0.55                 |
| Height (cm)      | 128.61          | 6.44                   | 129.19                 | 5.43     | 126.73              | 6.54                   | 0.06                 |
| Weight (kg)      | 28.60           | 5.78                   | 29.31                  | 5.67     | 26.41               | 4.50                   | 0.01                 |
| Body mass index  | 17.18           | 2.52                   | 17.45                  | 2.46     | 16.34               | 1.65                   | 0.01                 |
| Waist circumference (cm) | 60.67 | 6.75                   | 60.76                  | 6.48     | 58.33               | 4.90                   | 0.02                 |
| Mid-abdominal skinfold (mm) | 6.09 | 3.80                   | 6.78                   | 4.20     | 4.66                | 3.60                   | 0.20                 |
| Suprailliac skinfold (mm) | 6.03 | 2.53                   | 5.66                   | 2.87     | 3.44                | 2.80                   | 0.03                 |
| Subcapular skinfold (mm) | 7.72 | 4.38                   | 7.82                   | 4.17     | 6.44                | 1.91                   | 0.04                 |
| Truncal fat mass (mm) | 8.94 | 5.26                   | 9.25                   | 5.36     | 7.46                | 3.18                   | 0.06                 |
| Serum insulin (mU/l) | 7.31 | 4.80                   | 8.01                   | 4.21     | 6.16                | 2.72                   | 0.06                 |
| Serum fasting glucose (mm/l) | 4.47 | 0.47                   | 4.46                   | 0.38     | 4.44                | 0.45                   | 0.87                 |
| Cardiorespiratory fitness score† | 18.47 | 8.96                   | 18.49                  | 8.11     | 17.68               | 7.56                   | 0.79                 |
| Physical activity score‡ | 60.35 | 22.63                  | 60.34                  | 23.34    | 61.07               | 21.28                  | 0.97                 |

*Data presented as median and interquartile range.
†Cardiorespiratory fitness score (CRF) = number of laps completed in shuttle test.
‡Physical activity score (PA) = number of steps/minutes pedometer worn.
§Analysis of Variance (unadjusted). χ² analysis used for sex.

**Table 2.** Lipid and body size characteristics in E4-containing and Not E4-containing APOE genotype groups.

|                  | E4 containing (n = 75) | Not E4-containing (n = 208) | p-value† |
|------------------|------------------------|-----------------------------|---------|
|                  | Mean                   | SD                          | Mean     | SD       | Mean                 | SD       | p-value† |
| Body mass index  | 16.34                  | 1.65                        | 17.23    | 2.50     | 0.004               |
| Waist circumference (cm) | 58.33 | 4.90                   | 60.69    | 6.68     | 0.006               |
| Truncal fat mass (mm) | 7.46 | 3.18                   | 9.00     | 5.27     | 0.02                |
| Serum Total Cholesterol (mmol/l) | 4.45 | 0.70                   | 4.28     | 0.69     | 0.08                |
| Serum LDL-cholesterol (mmol/l) | 2.75 | 0.66                   | 2.56     | 0.63     | 0.03                |
| Serum HDL-cholesterol (mmol/l) | 1.53 | 0.32                   | 1.56     | 0.34     | 0.58                |
| Serum HDL/total cholesterol ratio | 0.35 | 0.08                   | 0.37     | 0.08     | 0.07                |
| Serum triglycerides (mmol/l)* | 0.76 | 0.60, 0.97              | 0.70     | 0.57, 0.92 | 0.37               |

†Linear regression (unadjusted).
*Data presented as median and interquartile range.
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Given that insulin resistance and obesity appear intrinsically linked, we performed further analyses to consider the role of insulin in the identified associations and interactions. None of the observed relationships were materially altered by adjustment for insulin. Particularly, the association of APOE4 and BMI was still evident only in the low-fit group following adjustment for insulin (low-fit p = 0.001; high-fit p = 0.71). Therefore, the effect of APOE4 and fitness on BMI appeared independent of mechanisms related to serum insulin.

Similar associations are seen for other measures of adiposity

We performed similar analyses on truncal fat mass and waist circumference, including association with APOE4, adjustment for confounders, and interaction with CRF, and observed similar associations (data not shown). Therefore, these similar relationships demonstrate consistence in the pattern of findings not only for BMI but across various measures of adiposity.

Discussion

This cohort sample incorporates a rare combination of childhood measures, including adiposity, APOE genotype, blood lipid profile, and PA and CRF. Using this study, we have identified that APOE4 appears to be associated with reduced adiposity in children. Additionally, this effect is modified by CRF; in children of lower CRF, APOE4 seems to predispose to lower adiposity, but also to a more atherogenic serum lipid profile. These findings show the importance of examining APOE, adiposity and blood lipids in the context of related PA and fitness.

Table 3. Interaction between APOE genotype and fitness in determining BMI.

| Fitness | APOE | n   | Mean (SD) | Mean difference (95% CI)* | P value |
|---------|------|-----|-----------|---------------------------|---------|
| High    | Not E4-containing | 104 | 16.39 (1.69) |                           |         |
|         | E4-containing     | 34  | 16.44 (1.68) | 0.074 (-0.59, 0.73)       | 0.825   |
| Low     | Not E4-containing | 104 | 18.07 (2.88) |                           |         |
|         | E4-containing     | 41  | 16.25 (1.65) | -1.78 (-2.74, -0.83)      | <0.001  |

*Linear regression adjusted for age and sex.
†Difference in the association between E4 and BMI by fitness category.

Table 4. Associations between BMI and blood lipids in the low fitness group by absence (n = 104) or presence (n = 41) of an APOE4 allele.

| Lipid          | No APOE4 allele | APOE4 allele |
|----------------|-----------------|--------------|
|                | Regression coefficient (95% CI)* | P value | Regression coefficient (95% CI)* | P value |
| Total Cholesterol | 0.60 (-0.19, 1.39) | 0.133       | -0.04 (-1.01, 0.93) | 0.94 |
| LDL-C          | 1.06 (0.15, 1.98) | 0.023       | 0.22 (-0.58, 1.03) | 0.58 |
| HDL-C          | -1.47 (-3.20, 0.27) | 0.097       | -0.68 (-2.23, 0.85) | 0.37 |
| HDL/Total-C ratio | -11.38 (-19.08, -3.69) | 0.004       | -3.46 (-10.25, 3.33) | 0.31 |
| Log triglycerides | 2.55 (1.03, 4.08) | 0.001       | 1.03 (-0.58, 2.63) | 0.20 |

Fitness measured by shuttle test and dichotomised at the median. There were no associations between BMI and blood lipids for either of the high-fit-APOE4 genotype combinations.

*Adjusted for age and sex.

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together, these data suggest that a possible mechanism through which E4 may protect against adiposity is via a reduction in the ability of adipocytes to accumulate TG.

PA was recently demonstrated to modify the effect of obesity related genes in adults [12]. PA has also been shown to modify the effect of APOE genotype on lipids, particularly LDL-C, in children and adults [7,13]. We saw little evidence of such an interaction when considering both an objective, and a subjective measure of PA, although the ability to fully test this was limited by the fact that we collected objective PA data at only one time-point in a single day. However, a novel aspect of this study was our ability to also examine the effect of CRF on the child APOE-adiposity association. This is of relevance because CRF appears more important in controlling cardiovascular disease risk factors than PA [22]. Our data concurs with recent work demonstrating that the association between CRF and PA is generally weak [23], especially in children [24]. It is likely that CRF is determined not only by a number of environmental factors that includes PA, but also by genetic factors [25]. Thus there is a clear need to consider PA and CRF separately. We found no interaction between PA and APOE genotype in determining BMI. However, we did find that APOE4 was strongly associated with lower BMI only in those of lower CRF, and had little effect on BMI in those of higher CRF. This suggests that the mode of action through which APOE4 exerts its apparent protective effect against adiposity may only be relevant in those who are less fit.

We also examined the relationship between blood lipids and BMI in children grouped by APOE variant and fitness. There was little association between lipids and BMI, except in the low-fit, non-E4 allele group, where BMI was associated with TG, LDL-C, and HDL/total-C ratio. We suggest that in children of higher fitness, lipid may be more efficiently removed from circulation via, for example, muscle metabolism, and in those carrying APOE4, storage of lipid by adipocytes is reduced. Only in children who are of lower fitness and who lack APOE4 may be free to take up and store lipids at a rate that is mainly dependent on circulating lipid levels.

The relationship between APOE4, circulating LDL-C, cardiovascular risk, and BMI warrants further scrutiny. It is well established that APOE4 predisposes to higher circulating LDL-C, along with higher cardiovascular risk [2]. In the THS, we confirmed the association of E4 with higher LDL-C, however the study design precluded assessment of cardiovascular risk. The lower BMI seen in E4 carriers appears somewhat counterintuitive to higher cardiovascular risk that might be predicted to be present in these individuals. But the existence of a direct relationship between high BMI, as one of a web of metabolic syndrome factors, and increased cardiovascular risk, is unclear [26,27,28,29]. Barriers to the deposition of lipid into adipocytes may result in lower BMI, but may also drive higher circulating levels of lipids such as LDL-C and thus a more detrimental atherogenic lipid profile and higher cardiovascular risk. Thus, it is possible that while APOE4 might confer protection from fatness, it may also confer higher risk of cardiovascular disease.

It is also pertinent to mention that, despite recent large scale genome-wide association analyses [11], association of APOE genotype with human adiposity has not, to our knowledge, been reported previously. We suggest that this may be because genome-wide association studies have by-and-large focussed on adult obesity. We also suggest that the effects of APOE on adiposity may not be strongly and replicably apparent without both specific consideration of the E4 allele, and the interaction of E4 with CRF. Additionally, the lack of consistency of association of APOE genotype with various lipids such as TGs and HDL-C across numerous studies [2,30,31,32,33] may be due to the interacting effect of BMI and CRF, the latter of which is rarely taken into consideration in such analyses. Our findings require independent confirmation in cohorts where data on both APOE genotype and CRF is available. However, we suggest our data demonstrates the importance of the consideration of environmental factors in tandem with genetic factors, in order to continue to progress our understanding of the architecture of complex diseases and phenotypes [34].

It is interesting to speculate as to whether APOE may be a ‘thrifty’ gene during times of food abundance. Thrifty genes are historically advantageous in times of famine, but are rendered detrimental by modern high fat diets and sedentary lifestyles [35]. In Caucasians, as in most populations, the APOE3 allele is the most frequent, and is in high frequency in the non-APOE4-containing genotype carriers to which we compared our E4-containing carriers. Our data suggests that E3 (and also possibly E2) may provide more efficient fat deposition than E4, and may be the thrifty allele(s) that in the face of high fat diets and low fitness levels, now predispose to higher BMI. The modern APOE4 allele might protect against fat deposition, however it appears to also predispose to a more atherogenic lipid profile [2], thus leading to a higher risk of cardiovascular disease in APOE4 carriers.

In conclusion, in 8 yr old children from the TIHS, APOE4 is associated with lower BMI. The relationship between APOE4 and lower BMI is potentiated by lower CRF. We propose that, in those of lower CRF, APOE4 compensates for the lack of the protective effect of fitness from increased adiposity. Based on animal model studies, the mechanism through which APOE4 may protect against increased adiposity may involve a decreased ability of E4-expressing adipocytes to take up, synthesise, and/or store TGs. At a future clinical level, we suggest that assessment of child CRF and APOE4 genotype may potentially define a subgroup that is more vulnerable to increased adiposity, and therefore more at risk of later obesity-related disease. Although our sample size is relatively small, our data provide strong impetus for further examination of the role of APOE in determining adiposity in larger studies of both children and adults.

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Author Contributions

Conceived and designed the experiments: ALP TD. Performed the experiments: JD JC. Analyzed the data: JE AP ALP EW. Wrote the paper: JE ALP AP EW JC JD TD.

References

1. Huang ZH, Minshull RD, Maczzone T (2009) Mechanism for endogenously expressed ApoE: modulation of adipocyte very low density lipoprotein metabolism: role in endocytic and lipase-mediated metabolic pathways. J Biol Chem 284: 31512–31522. 2. Bennet AM, Di Angelantonio E, Ye Z, Wensley F, Dahlin A, et al. (2007) Association of apolipoprotein E genotypes with lipid levels and coronary risk. Jama 298: 1300–1311.
3. Isasi CR, Deckelbaum RJ, Tracy RP, Sarr T, Berglund L, et al. (2003) Physical fitness and C-reactive protein level in children and young adults: the Columbia University BioMarkers Study. Pediatrics 111: 332–338.

4. Lehtimäki T, Moilanen T, Viikari J, Akerblom HK, Ehnholm C, et al. (1990) Apolipoprotein E phenotypes in Finnish youth: a cross-sectional and 6-year follow-up study. J Lipid Res 31: 487–495.

5. Lehtimäki T, Perkka K, Viikari J, Ehnholm C, Akerblom HK, et al. (1994) Apolipoprotein E phenotypes and serum lipids in newborns and 3-year-old children: the Cardiovascular Risk in Young Finns Study. Pediatrics 94: 489–493.

6. Medina-Urrutia AX, Cardoso-Saldana GC, Zamora-Gonzalez J, Liria YK, Posadas-Romero C (2004) Apolipoprotein E polymorphism is related to plasma lipids and apolipoproteins in Mexican adolescents. Hum Biol 76: 605–614.

7. Taimela S, Lehtimäki T, Perkka KV, Rasannen L, Viikari JS (1996) The effect of physical activity on serum total and low-density lipoprotein cholesterol concentrations varies with apolipoprotein E phenotype in male children and young adults: The Cardiovascular Risk in Young Finns Study. Metabolism 45: 797–803.

8. Huang ZH, Reardon CA, Mazzone T (2006) Endogenous ApoE expression modulates adipocyte triglyceride content and turnover. Diabetes 55: 3394–3402.

9. Arbones-Mainar JM, Johnson LA, Altenburg MK, Maeda N (2008) Differential modulation of diet-induced obesity and adipocyte functionality by human apolipoprotein E3 and E4 in mice. Int J Obes (Lond) 32: 1595–1605.

10. Vokíč KA, Barkley RA, Hutchinson RG, Mosley TH, Heiss G, et al. (2006) Apolipoprotein E polymorphisms predict low density lipoprotein cholesterol levels and carotid artery wall thickness but not incident coronary heart disease in 1249 ARIC study participants. Am J Epidemiol 164: 342–348.

11. Valley AJ, Asher JE, Frosqul P (2009) The genetic contribution to non-syndromic human obesity. Nat Rev Genet 10: 431–442.

12. Li S, Zhao JH, Luan J, Ekelund U, Luben RN, et al. (2010) Physical activity associated with the gene predisposition to obesity in 20,000 men and women from EPIC-Norfolk prospective population study. PloS Med 7.

13. Hagberg JM, Wilund KR, Ferrell RE. (2000) APO E gene and gene-environment effects on plasma lipoprotein-lipid levels. Physiol Genomics 4: 101–108.

14. Dwyer T, Blizzard L, Venn A, Stankovich JM, Ponsonby AL, et al. (2002) Syndrome X in 8-year-old Australian children: stronger associations with current body fatness than with infant size or growth. Int J Obes (Lond) 32: 1595–1605.

15. Jones G, Dwyer T (1998) Bone mass in prepubertal children: gender differences and the role of physical activity and sunlight exposure. J Clin Endocrinol Metab 83: 4274–4279.

16. Dwyer T, Ponsonby AL, Newman NM, Gibbons LE (1991) Prospective cohort study of prone sleeping position and sudden infant death syndrome. Lancet 337: 1244–1247.

17. d’Espaignet ET, Dwyer T, Newman NM, Ponsonby AL, Candy SG (1990) The development of a model for predicting infants at high risk of sudden infant death syndrome in Tasmania. Paediatr Perinat Epidemiol 4: 422–433.

18. Dwyer T, Blizzard L, Patterson B, Ponsonby AL, Martin K, et al. (2008) Association between birth weight and adolescent systolic blood pressure in a caucasian birth cohort differs according to skin type, CRH promoter or 11beta-HSD2 genotype. Arch Dis Child 93: 760–767.

19. Leger LA, Mercier D, Gadouey C, Lambert J (1988) The multistage 20 metre shuttle run test for aerobic fitness. J Sports Sci 6: 93–101.

20. van Mechelen W, Hlobil H, Kemper HC (1996) Validation of two running tests as estimates of maximal aerobic power in children. Eur J Appl Physiol Occup Physiol 55: 503–506.

21. Kypri KE, Karagiannides I, Fotiadou EH, Karavia EA, Brinkmeier MS, et al. (2009) Mechanisms of obesity and related pathologies: role of apolipoprotein E in the development of obesity. Plight J 276: 5720–5728.

22. Sassen B, Cornelissen VA, Kiers H, Wintink H, Kol G, et al. (2009) Physical fitness matters more than physical activity in controlling cardiovascular disease risk factors. Eur J Cardiovasc Prev Rehabil 16: 617–683.

23. Nokes N (2009) Relationship between physical activity and aerobic fitness. J Sports Med Phys Fitness 49: 136–141.

24. Kristensen PL, Moeller NC, Korsholm L, Kølle E, Wedderkopp N, et al. (2010) The association between aerobic fitness and physical activity in children and adolescents: the European youth heart study. Eur J Appl Physiol Published online 11 May; DOI 10.1007/s00424-010-1491-x.

25. Macarthur DG, North KN (2005) Genes and human elite athletic performance. Hum Genet 116: 331–339.

26. Bluhler M (2010) The distinction of metabolically ‘healthy’ from ‘unhealthy’ obese individuals. Curr Opin Lipidol 21: 39–45.

27. Eckel RH, Grundy SM, Zimet FF (2005) The metabolic syndrome. Lancet 365: 1415–1428.

28. Lavie CJ, Milan KV, Ventura HO (2009) Obesity and cardiovascular disease: risk factor, paradox, and impact of weight loss. J Am Coll Cardiol 53: 1925–1932.

29. Sabin MA, Clemens SL, Safirry R, McCallum Z, Campbell MW, et al. (2010) New directions in childhood obesity research: how a comprehensive biorepository will allow better prediction of outcomes. BMC Med Res Methodol 10: 100.

30. Chasan-Taber L, Pare G, Mora S, Hopewell JC, Peloso G, et al. (2009) Forty-three loci associated with plasma lipoprotein size, concentration, and cholesterol content in genome-wide analysis. PLoS Genet 5: e1000730.

31. Chasan-Taber L, Pare G, Zee KY, Parker AN, Cook NR, et al. (2008) Genetic loci associated with plasma concentration of low-density lipoprotein cholesterol, high-density lipoprotein cholesterol, triglycerides, apolipoprotein A1, and Apolipoprotein B among 6382 white women in genome-wide analysis with replication. Cere Cardiovasc Genet 1: 21–30.

32. Katheresan S, Meander O, Guidacci C, Sarti A, Burt NP, et al. (2008) Six new loci associated with blood low-density lipoprotein cholesterol, high-density lipoprotein cholesterol or triglycerides in humans. Nat Genet 40: 189–197.

33. Katheresan S, Willet C, Peloso GM, Demissie S, Musunuru K, et al. (2009) Common variants at 30 loci contribute to polygenic dyslipidemia. Nat Genet 41: 56–65.

34. Manolio TA, Collins FS, Cox NJ, Goldstein DB, Hindorff LA, et al. (2009) Finding the missing heritability of complex diseases. Nature 461: 747–753.

35. Neel JV (1962) Diabetes mellitus: a ‘thrifty’ genotype rendered detrimental by a change in lifestyle. Science 138: 222–223.
