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Metabolic Profiling of Adiponectin Levels in Adults
Mendelian Randomization Analysis

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Background—Adiponectin, a circulating adipocyte-derived protein, has insulin-sensitizing, anti-inflammatory, antiatherogenic, and cardiomyocyte-protective properties in animal models. However, the systemic effects of adiponectin in humans are unknown. Our aims were to define the metabolic profile associated with higher blood adiponectin concentration and investigate whether variation in adiponectin concentration affects the systemic metabolic profile.

Methods and Results—We applied multivariable regression in ≤5909 adults and Mendelian randomization (using *cis*-acting genetic variants in the vicinity of the adiponectin gene as instrumental variables) for analyzing the causal effect of adiponectin in the metabolic profile of ≤37 545 adults. Participants were largely European from 6 longitudinal studies and 1 genome-wide association consortium. In the multivariable regression analyses, higher circulating adiponectin was associated with higher high-density lipoprotein lipids and lower very-low-density lipoprotein lipids, glucose levels, branched-chain amino acids, and inflammatory markers. However, these findings were not supported by Mendelian randomization analyses for most metabolites. Findings were consistent between sexes and after excluding high-risk groups (defined by age and occurrence of previous cardiovascular event) and 1 study with admixed population.

Conclusions—Our findings indicate that blood adiponectin concentration is more likely to be an epiphenomenon in the context of metabolic disease than a key determinant. **(*Circ Cardiovasc Genet*. 2017;10:e001837. DOI: 10.1161/CIRCGENETICS.117.001837.)**

Key Words: adiponectin ■ cardiovascular disease ■ insulin ■ Mendelian Randomization Analysis ■ metabolism ■ metabolomics

The recognition that adipose tissue is an endocrine organ raised new prospects for discovering adipose-derived products that could be valuable drug targets for the treatment and prevention of cardiometabolic diseases. In this context, adiponectin, a 30 kDa protein largely produced by mature adipocytes, has been attracting widespread attention because of insulin-sensitizing, anti-inflammatory, antiatherogenic, and cardiomyocyte-protective properties demonstrated in animal models.[1]

See Clinical Perspective

However, human studies have yielded a far more complicated picture. Unlike most other adipokines, circulating adiponectin concentration is higher with lower adiposity.[2] In prospective observational studies in humans using multivariable regression, higher circulating adiponectin is associated with lower risk of type 2 diabetes mellitus,[3] hepatic dysfunction,[4] and metabolic syndrome[5] but higher mortality in patients with kidney disease, heart failure, previous cardiovascular disease, or general elderly cohorts[6–9]; this different direction of effect between risk of incident disease and mortality among high-risk groups has been called the adiponectin paradox.[10]

Given the complex metabolic derangements that might participate in and compensatory changes that might occur in response to human diseases, the association between adiponectin concentration and cardiometabolic biomarkers and disease end

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points might be explained by reverse causality (where disease status could alter adiponectin concentration) or residual confounding (where adiponectin could be a marker of another causal factor, such as adiposity or insulin resistance).[11] Classical multivariable regression studies cannot distinguish causal from noncausal associations, and randomized controlled trials specifically targeting adiponectin are not possible in the absence of a specific therapeutic targeting adiponectin concentration or function.

Mendelian randomization uses genetic variants (mostly single-nucleotide polymorphisms [SNPs]) that are robustly related to the risk factor of interest as tools to assess its role in causing disease.[12] The random allocation of parental alleles at meiosis should theoretically reduce confounding in genetic association studies, and this has been shown to be the case[13]; the unidirectional flow of biological information from genetic variant to phenotypes avoids reverse causality. Mendelian randomization has been used in clinical research to investigate potential etiologic mechanisms, such as the causal effects of low-density lipoprotein cholesterol (LDL-C),[14] systolic blood pressure,[15] and CRP (C-reactive protein)[16] on coronary heart disease, validate and prioritize novel drug targets, such as IL-6 (interleukin-6) receptor,[17] and increase understanding of current therapies, for example, statins.[18]

Previous Mendelian randomization studies indicate that circulating adiponectin is a consequence of low insulin sensitivity,[19] but whether adiponectin concentration is also a cause of insulin sensitivity is uncertain.[19–21] Using Mendelian randomization in a study of 63 746 coronary heart disease cases and 130 681 controls, we have recently shown that adiponectin may not be causally related to coronary heart disease.[22] Although multivariable analyses show that higher adiponectin concentration is associated with lower glycated hemoglobin, insulin, triglycerides (TG), and higher high-density lipoprotein cholesterol (HDL-C), using Mendelian randomization, we found little evidence that these were causal.[22] Whether adiponectin is associated with systemic metabolic profile, and, if it is, what aspects of these associations are causal is unknown. A broader interrogation of the metabolic effects of adiponectin through high-throughput profiling of metabolic status could provide valuable insights into whether adiponectin is a noncausal biomarker or causally important in the pathophysiology of some human diseases.[23]

We combined genotype, adiponectin, and metabolomics profile data from 6 longitudinal studies and 1 genome-wide association consortium with the aim of (1) defining the metabolic signature of blood adiponectin concentration and (2) investigating whether variation in adiponectin concentration is causally related to the systemic metabolic profile.

Methods

Study Populations

The metabolic profile associated with blood adiponectin concentration was examined from 7 data sources: PEL82 (the 1982 Pelotas Birth Cohort), including adults aged 30 years old born in the city of Pelotas, Brazil, in 1982[24,25]; BWHHS (the British Women's Heart and Health Study), including UK women aged 60 to 79 years old at recruitment in 2000[26]; WHII study (the Whitehall II), including UK government workers aged 45 to 69 years at phase 5 clinical assessment in 1997 to 1999[27]; the CaPS (Caerphilly Prospective Study), including men aged 52 to 72 years at phase III in 1989 to 1993[28]; a case–control study nested in UKCTOCS (the United Kingdom Collaborative Trial of Ovarian Cancer Screening), including UK postmenopausal women aged 50 to 74 years at recruitment in 2001 to 2005[29]; the ALSPAC-M (Cohort of Mothers From the Avon Longitudinal Study of Children and Parents), including UK women aged 34 to 63 years old at clinical assessment in 2009 to 2011[30]; and a metabolomics genome-wide association consortium (hereafter referred to as Metabolomics consortium), including European adults with mean age of 45 years old from 14 cohorts.[31] Individual-level data were available to investigators from PEL82, BWHHS, WHII, CaPS, UKCTOCS, and ALSPAC-M. Individual-level study data cannot be made available to other researchers for purposes of reproducing the results or replicating the procedure. Summary-level data are publicly available from the Metabolomics consortium (URL: http://www.computationalmedicine.fi/data/NMR_GWAS/).

All study participants provided written informed consent, and study protocols were approved by the local ethics committees (ethical approval for ALSPAC was also obtained from the ALSPAC Ethics and Law Committee). Studies' characteristics are summarized in Table 1. We examined (possibly causal) associations of adiponectin with systemic metabolic profiles using 2 approaches—conventional multivariable regression and Mendelian randomization analyses. Studies must have both adiponectin and measures of some of the outcomes (but do not need genetic data) to contribute to multivariable regression analyses and must have relevant genetic variants and outcomes (but do not need adiponectin concentration data) to contribute to Mendelian randomization analyses. Figure 1 shows how the different data sources contributed to the 2 approaches.

Metabolite Quantification

A high-throughput serum nuclear magnetic resonance (NMR) spectroscopy platform was used to quantify ≤150 metabolic measures and 83 derived measures (ratios) in each study. The experimental protocols, including sample preparation and NMR spectroscopy methods, have been described in detail elsewhere[32,33] and are described briefly in Methods in the Data Supplement. Sixty-six of 150 metabolic measures were selected for this study aimed at broadly representing the systemic metabolite profile, as previously reported by Würtz et al,[34] including lipoprotein traits (lipid content, particle size, and Apo [apolipoproteins]), fatty acids, amino acids, glycolysis-related metabolites, ketone bodies, fluid balance (albumin and creatinine), and inflammatory markers (glycoprotein acetyls). The remaining 84 metabolic measures from the NMR platform are related to other lipid fractions (esterified and free cholesterol, total cholesterol, TG, and phospholipids) and particle concentration from 14 lipoprotein subclasses. As these 84 metabolic measures are highly correlated with ≥1 of the 66 selected metabolic measures, they were not included in the main analysis (as they would not bring additional information) and were presented in the Data Supplement. Eight additional measures, not obtained from the NMR platform, were included: CRP, IL-6, fibrinogen, blood viscosity, insulin, glycated hemoglobin, and systolic blood pressure and diastolic blood pressure. PEL82 did not have data on metabolic measures from NMR platform and contributed data to analyses of conventional lipid risk factors (total cholesterol, HDL-C, LDL-C, and TG) and some of the additional measures described (CRP, glycated hemoglobin, systolic blood pressure, and diastolic blood pressure). Adiponectin was assayed using an ELISA in PEL82, BWHHS, and WHII. Data on adiponectin level were not available from CaPS, UKCTOCS, ALSPAC-M, and the Metabolomics consortium. Blood samples used for adiponectin, NMR metabolites, and other blood-based outcomes assays were taken after overnight or minimum 6-hour fast in BWHHS, CaPS, and ALSPAC-M and on nonfasting samples in PEL82 and UKCTOCS. In WHII, participants attending the morning clinic were asked to fast overnight and those attending in the afternoon were asked to have a light, fat-free breakfast before 08:00 hours. The vast majority of samples contributing to the Metabolomics consortium were fasting samples.

Genotyping

BWHHS, CaPS, WHII, and UKCTOCS participants were genotyped using Metabochip, a platform comprising 200 000 SNPs, which cover the loci identified by genome-wide association studies in cardiometabolic

Table 1. Characteristics of Participating Studies

	PEL82	BWHHS	WHII	CaPS	UKCTOCS Case–Control*	ALSPAC-M	Metabolomics Consortium
Study design	Cohort	Cohort	Cohort	Cohort	Nested case–control study	Cohort	14 cohorts
Setting	Brazil	United Kingdom	United Kingdom	United Kingdom	United Kingdom	United Kingdom	Europe
Recruitment setting	Hospitals	General practices	Workplace	General practices and electoral register	Hospitals	Media information, community locations, and health services	Multiple settings
Participants	Adults aged 30-y-old born in the city of Pelotas in 1982	Women aged 60–79 y old at recruitment	Civil servants aged 45–69 y at phase 5	Men aged 52–72 y old at phase III	Postmenopausal women aged 50 y old and above at recruitment	Women aged 34–63 y old residing in a defined area in the South West of England that gave birth between April 1, 1991 to December 31, 1992	Adults recruited for multiple studies (mean age: 45 y old)
Phase of data collection	2012 follow-up	Recruitment (1999–2001)	Phase 5 (1997–1999)	Phase III (1989–1993)	Recruitment (2001–2005)	Follow-up clinic assessment (2009–2011)	Data collected in different phases according to each study
Blood samples fasted	No	Yes	Mixed	Yes	No	Yes	Yes (for the vast majority of blood samples)
No. of individuals at data collection phase	3701	4286	7870	2154	4867	4834	25 072
No. of individuals for adiponectin	3541	498	2662	0	0	0	0
No. of individuals for metabolites	3530†	3780	4641	1225	4813	4138	25 072
No. of individuals for other phenotypes‡	3530–3617	3636–3964	4620–4874	608–1207	0	4092–4568	…
No. of individuals for genotype	2898	1980	3078	1349	1472	8672§	25 072
No. of individuals for MV analyses	2753–2762	396–497	2442–2656	…	…	…	…
No. of individuals for MR analyses	2753–2783	1656–1967	2773–3020	101–1211	1067–1435	2548–3375	12 978–24 924
Website	http://www.epidemio-ufpel.org.br/site/content/coorte_1982-en/index.php	http://www.ucl.ac.uk/british-womens-heart-health-study	http://www.ucl.ac.uk/whitehallII	http://www.bristol.ac.uk/social-community-medicine/projects/caerphilly/about/	http://www.instituteforwomenshealth.ucl.ac.uk/womens-cancer/gcrc/ukctocs	http://www.bristol.ac.uk/alspac/	http://www.computationalmedicine.fi/data/NMR_GWAS/

ALSPAC-M indicates the Avon Longitudinal Study of Children and Parents-Mothers' Cohort; BWHHS, British Women's Heart and Health Study; CaPS, the Caerphilly Prospective Study; MR, Mendelian randomization; MV, multivariable; PEL82, 1982 Pelotas Birth Cohort; UKCTOCS, Case–Control Study Nested in the United Kingdom Collaborative Trial of Ovarian Cancer Screening; and WHII study, Whitehall II.

*The nested case–control study consisted of a subsample (n=4867) of the original UKCTOCS randomized controlled trial (n=202 638 recruited individuals).

†For PEL82, the only metabolites available were glucose, total cholesterol, high-density lipoprotein cholesterol, low-density lipoprotein cholesterol, and TG.

‡Other phenotypes include systolic and diastolic blood pressure, glycohemoglobin, C-reactive protein, interleukin-6, fibrinogen, and blood viscosity.

§DNA samples were collected for the whole cohort in prior phases of ALSPAC-M cohort.

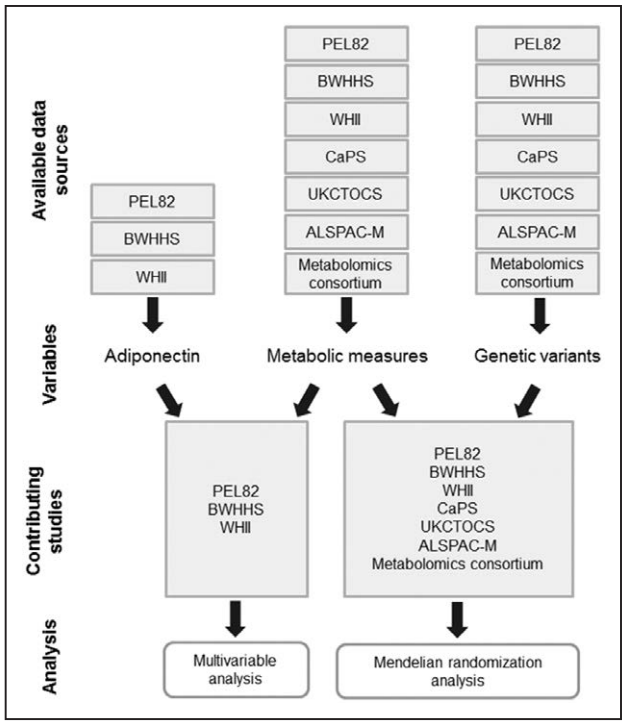

Figure 1. Schematic representation of studies contributing to each analytic approach. From the available data sources, 3 had data on adiponectin and metabolic measures and could contribute to multivariable analysis (PEL82 [1982 Pelotas Birth Cohort], BWHHS [British Women's Heart and Health Study], and WHII study [Whitehall II]), and all had data on genetic variants and metabolic measures and could contribute to Mendelian randomization analysis (PEL82, BWHHS, WHII, CaPS [the Caerphilly Prospective Study], UKCTOCS [the United Kingdom Collaborative Trial of Ovarian Cancer Screening], ALSPAC-M [Cohort of Mothers From the Avon Longitudinal Study of Children and Parents], and Metabolomics consortium).

diseases and rare variants from the 1000 Genomes Project.[35] Quality control criteria and imputation using 1000 Genomes European ancestry reference samples have been previously described for studies within UCLEB consortium (University College London, London School of Hygiene & Tropical Medicine, University of Edinburgh and University of Bristol).[36] In ALSPAC-M, 557 124 SNPs were directly genotyped using Illumina human660W quad. For quality control, SNPs were excluded if missingness >5%, Hardy–Weinberg equilibrium P value $<1\times10^{-6}$, or minor allele frequency <1%, and samples were excluded if missingness >5%, indeterminate X chromosome heterozygosity, extreme autosomal heterozygosity, or showing evidence of population stratification. Imputation was performed using 1000 genomes reference panel (Phase 1, Version 3; phased using ShapeIt v2.r644, haplotype release date December 2013) and Impute V2.2.2. For PEL82, genotyping was performed by using the Illumina HumanOmni2.5-8v1 array (Illumina Inc), and ≈2 500 000 SNPs were genotyped.[37] For PEL82, quality control criteria have been previously described,[37] and imputation was performed in 2 steps: first, genotypes were phased using SHAPEIT; then, IMPUTE2 was used for the actual imputation. For autosomal and X chromosome SNPs, 1000 Genomes Phase I integrated haplotypes (December 2013 release) and 1000 Genomes Phase I integrated variant set (March 2012 release), respectively, were used. For PEL82, ancestry-informative principal components were based on 370 539 SNPs shared by samples from the HapMap Project, the Human Genome Diversity Project, and PEL82.[38] Cohorts contributing to the Metabolomics consortium used different SNP arrays; nongenotyped SNPs were imputed using a 1000 Genomes Project March 2012 version and SNPs with accurate imputation (proper info >0.4) and minor allele count >3 were combined in fixed-effects meta-analysis using double genomic control correction. Further details can be found in the consortium publication.[31]

Other Covariates

Anthropometric variables (weight and height) were measured in each study using standard procedures, and body mass index was calculated as weight (kg)/height (m)^2. Demographic and smoking status information was obtained through questionnaires.

Data Analysis

Before multivariable and genetic analyses, each study adjusted metabolic measures for age, sex, and, if applicable, place of recruitment (BWHHS and UKCTOCS) or principal components of genomic ancestry (PEL82 and some studies contributing to Metabolomics consortium), and the resulting residuals were transformed to normal distribution and standardized using inverse rank-based normal transformation. Pregnant women from PEL82 (n=73) and ALSPAC-M (n=12) were excluded. As the 74 analyzed metabolic measures are highly correlated, we adopted a similar strategy to the Metabolomics consortium[31] to correct for multiple testing by estimating the number of independent tests as the number of principal components that explained over 95% of variance in metabolic measures using data from the 2 studies (BWHHS and WHII) with the largest available number of metabolites (n=27 principal components in both studies). As a result, for both multivariable and Mendelian randomization analyses, we corrected for multiple testing using the Bonferroni method considering 27 independent tests (P=0.05/27≈0.0019). Analyses were conducted in Stata version 12.

Multivariable Regression Analysis

The conventional multivariable regression association of adiponectin with individual metabolites was estimated using a 2-stage individual participant meta-analysis. In the first stage, linear regression models were fitted for each study. In the second stage, study-specific estimates were meta-analyzed using DerSimonian and Laird random-effect model.[39] Heterogeneity across studies was assessed using I^2 (as a measure of the relative size of between-study variation and within-study error).[40] Three types of subgroup analyses were conducted: sex-stratified analysis, analysis excluding individuals with high risk of cardiometabolic disease (those that had experienced coronary artery disease or stroke or those older than 65 years), and analysis restricted to European studies (excluding PEL82).

Genetic Analyses

Four independent SNPs in the vicinity of *ADIPOQ* locus (±50 kb), previously identified to predict adiponectin levels, were selected[22,41] (details in Methods in the Data Supplement). These SNPs (rs6810075, rs16861209, rs17366568, and rs3774261) are estimated to explain ≈4% of variance in adiponectin concentration (details in Methods in the Data Supplement). Data for the association of each selected SNP with adiponectin concentration in the discovery sample of ADIPOGen, the largest consortium of genome-wide association studies for adiponectin, were downloaded from https://www.mcgill.ca/genepi/adipogen-consortium.

Association of Genetic Variants With Classical Confounders

The association between genetic variants and classical confounders (sex, age, ancestry [European versus non-European], current smoking [yes versus no], and body mass index) was examined for each study that provided individual-level data using logistic or linear regression models for binary or continuous variables, respectively.

Mendelian Randomization Analysis

To allow all participants with relevant genetic and metabolic measure data to contribute to analyses, even when adiponectin data were not available (as in CaPS, UKCTOCS, ALSPAC-M, and Metabolomics consortium), a 2-sample Mendelian randomization design was used, in which data for the association between genetic variants and adiponectin levels were obtained from an external data source, the ADIPOGen consortium.[42] The 2-sample Mendelian randomization is a recent extension to the

more conventional 1-sample Mendelian randomization and, when samples are independent, has the additional advantage of avoiding bias because of genetic variants correlating with confounders by chance (statistical overfitting).[43] The 2-sample Mendelian randomization estimates and respective SEs were obtained by combining SNP-specific Wald ratios, as described by Burgess et al[44] and detailed in Methods in the Data Supplement. Study-specific Mendelian randomization estimates were meta-analyzed using DerSimonian and Laird random-effect model.[39] Heterogeneity across studies was assessed using I^2.[40] Subgroup analyses were conducted considering individual-level (sex and risk of cardiometabolic disease) and study-level characteristics (European versus non-European studies). The Metabolomics consortium did not contribute to subgroup analysis of individual-level characteristics as only summary data were available.

Comparison Between Multivariable and Mendelian Randomization Analyses

Results from conventional multivariable and Mendelian randomization analyses for each metabolic measure were compared using the Z test (details in the Methods in the Data Supplement) and by estimating the correlation between multivariable and Mendelian randomization estimates across all metabolic measures. Power calculations for multivariable and Mendelian randomization analysis are available in Table I in the Data Supplement.

Results

The study included a median sample size of 3008 adults in the multivariable analysis (range: 2470–5909) and a median sample size of 29 146 adults in the Mendelian randomization analysis (range: 4647–37 545). Total sample size for each metabolite in multivariable and Mendelian randomization analysis can be found in Table II in the Data Supplement. Characteristics of participants and distribution of metabolites from each contributing study are listed in Table 2 and Table III in the Data Supplement.

Adiponectin and the Systemic Metabolic Profile

In the multivariable analysis, adiponectin was associated with 59 of 74 (80%) metabolites at nominal level ($P<0.05$) and 49 of 74 (66%) after correcting for multiple testing ($P<0.0019$). Overall, higher circulating adiponectin was associated with a healthier systemic metabolite profile. Blood adiponectin concentration was strongly related to multiple lipoprotein traits. With higher adiponectin concentration, lipid concentration was lower in very low-density lipoprotein (VLDL) subclasses and higher in HDL subclasses, except for small HDL. There was no strong evidence of circulating adiponectin associating with total lipid content in LDL subclasses or in intermediate-density lipoprotein, although adiponectin concentration was inversely associated with LDL-TG. Higher adiponectin was associated with lower concentration of cholesterol, TG, and lower mean particle diameter in VLDL, as well as higher cholesterol concentration and mean particle diameter in HDL. Higher adiponectin concentration was also associated with higher concentration of Apo AI and phospholipids and lower concentration of TG and diglycerides (Figure 2).

Higher circulating adiponectin was also associated with healthier glycemic status (lower glucose and insulin concentration), lower blood concentration of glycolysis-related metabolites (lactate and pyruvate), saturated fatty acids, systemic inflammatory markers (CRP, fibrinogen, IL-6, glycoprotein

Table 2. Characteristics of Studies' Populations

	PEL82	BWHHS	WHII	CaPS	UKCTOCS	ALSPAC-M	Metabolomics Consortium
%							
Male	49	0	72	100	0	0	45
White	75	100	93	100	97	97	NA*
Smoker	24	12	17	20	NA	11	NA
Overweight/obese	58	72	57	69	60	56	NA
Median (p25, p75)							
Age, y	30 (30, 30)	69 (64, 73)	55 (51, 61)	56 (53, 60)	66 (60, 70)	48 (45, 51)	45 (24, 61)†
Adiponectin, µg/mL	7.9 (5.2, 11.9)	15.8 (10.8, 21.5)	8.5 (6.1, 12)	NA	NA	NA	NA
Glucose, mmol/L	4.8 (4.4, 5.3)	4.7 (4.3, 5.1)	5 (4.7, 5.4)	3.8 (3.5, 4.2)	2.2 (1.7, 3.1)	4.4 (4.1, 4.7)	NA
HDL-C, mmol/L	1.5 (1.2, 1.7)	1.6 (1.4, 1.9)	1.5 (1.3, 1.7)	0.9 (0.7, 1)	1.6 (1.4, 1.9)	1.7 (1.5, 1.9)	NA
LDL-C, mmol/L	2.7 (2.3, 3.3)	2.3 (1.9, 2.8)	1.9 (1.6, 2.2)	1.6 (1.3, 1.9)	1.8 (1.4, 2.2)	1.5 (1.2, 1.8)	NA
TG, mmol/L	1.1 (0.8, 1.6)	1.5 (1.1, 2)	1.1 (0.9, 1.5)	1.5 (1.2, 2)	1.5 (1.1, 2.1)	0.9 (0.7, 1.2)	NA
SBP, mm Hg	120 (112, 130)	146 (130, 163)	121 (111, 133)	144 (130, 160)	NA	117 (110, 125)	NA
DBP, mm Hg	75 (69, 81)	79 (71, 87)	77 (70, 84)	84 (76, 92)	NA	71 (66, 77)	NA

ALSPAC-M indicates the Avon Longitudinal Study of Children and Parents-Mothers' Cohort; BWHHS, British Women's Heart and Health Study; CaPS, the Caerphilly Prospective Study; DBP, diastolic blood pressure; HDL-C, high-density lipoprotein cholesterol; LDL-C, low-density lipoprotein cholesterol; NA: not available; PEL82, 1982 Pelotas Birth Cohort; SBP, systolic blood pressure; TG, triglycerides; UKCTOCS, Case–Control Study Nested in the United Kingdom Collaborative Trial of Ovarian Cancer Screening; and WHII study, Whitehall II.

*Cohorts contributing to the Metabolomics consortium were of European origin.

†Overall mean age (and range of mean age across studies).

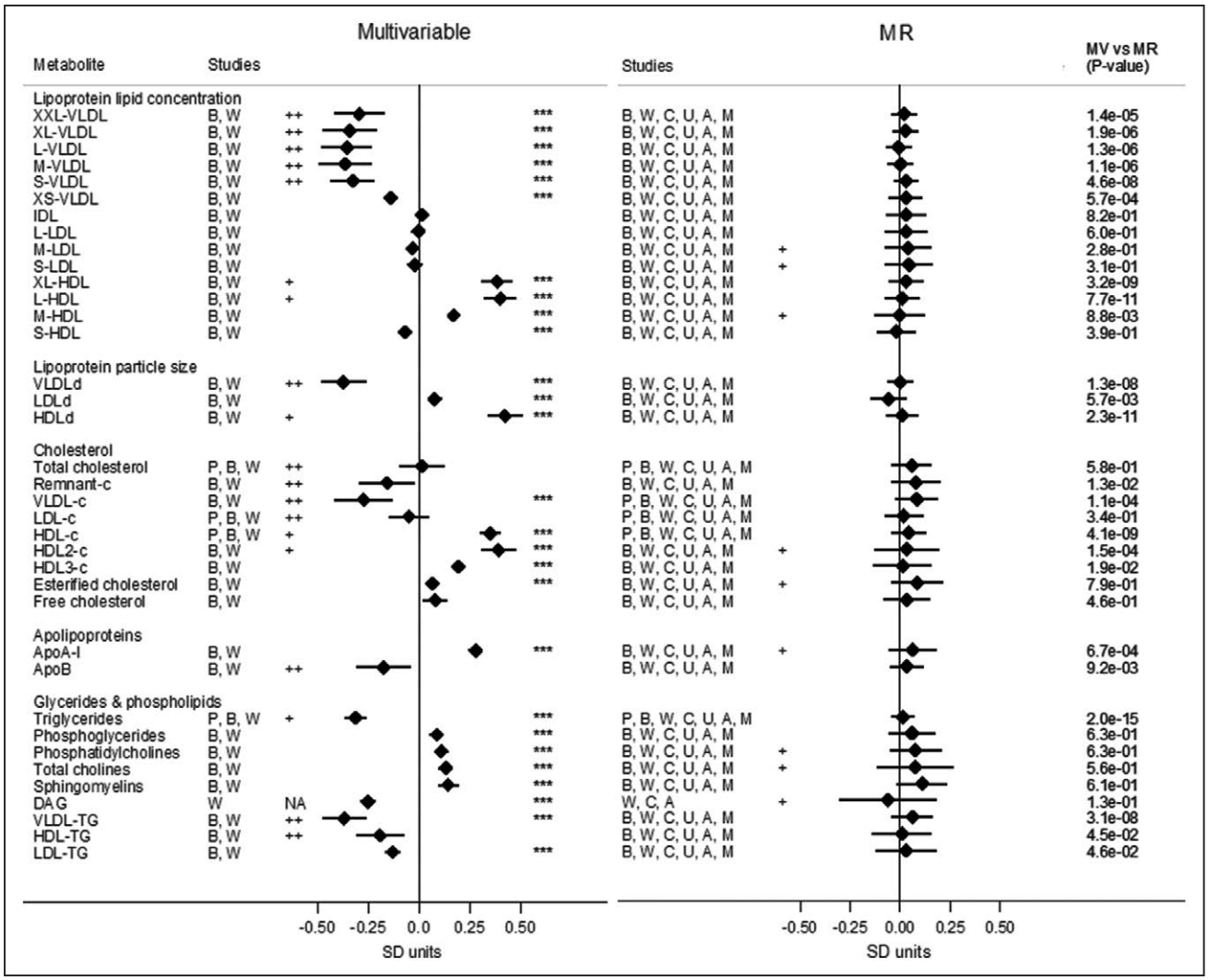

Figure 2. Association of lipoprotein traits with blood adiponectin levels from multivariable and Mendelian randomization (MR) analysis. Values are expressed as units of standardized metabolite concentration (and 95% CI [confidence interval]) per 1 U increment of standardized log adiponectin levels. *P* values for the association between adiponectin and metabolites are indicated by *** if lower than Bonferroni-adjusted threshold (*P* value <0.0019). Heterogeneity was considered substantial if I^2=50% to 75% (+) or high if I^2>75% (++). *P* values for the comparison between multivariable and MR estimates are displayed in the column MR vs MV (*P* value). Metabolic measures were adjusted for age, sex, and, if applicable, place of recruitment (BWHHS [British Women's Heart and Health Study] and UKCTOCS [the United Kingdom Collaborative Trial of Ovarian Cancer Screening]) or principal components of genomic ancestry (PEL82 [1982 Pelotas Birth Cohort] and some studies contributing to Metabolomics consortium), and the resulting residuals were transformed to normal distribution by inverse rank-based normal transformation. A indicates the Avon Longitudinal Study of Children and Parents-Mothers' Cohort; Apo, apolipoprotein; B, BWHHS; C, the Caerphilly Prospective Study; DAG, diglycerides; HDL, high-density lipoprotein; HDL-C, HDL cholesterol; HDLd, HDL particle mean diameter; IDL, intermediate-density lipoprotein; L-HDL, large HDL; L-LDL, large LDL; L-VLDL, large VLDL; LDL, low-density lipoprotein; LDL-C, LDL cholesterol; LDLd, LDL particle mean diameter; M-HDL, medium HDL; M-LDL, medium LDL; M-VLDL, medium VLDL; M, Metabolomics consortium; P, PEL82; S-HDL, small HDL; S-LDL, small LDL; S-VLDL, small VLDL; TG, triglycerides; U, UKCTOCS Nested Case–Control Study; VLDL, very-low-density lipoprotein; VLDL-C, VLDL cholesterol; VLDLd, VLDL particle mean diameter; W, Whitehall II Study; XL-HDL, very large HDL; XL-VLDL, very large VLDL; XS-VLDL, very small VLDL; and XXL-VLDL, extremely large VLDL.

acetyls, and blood viscosity), blood pressure, creatinine, and higher ketone bodies (acetoacetate). In addition, higher adiponectin concentration was associated with lower concentrations of free branched-chain amino acids (isoleucine, leucine, and valine), aromatic amino acids (phenylalanine and tyrosine), and alanine and higher concentration of glutamine (Figure 3).

In the multivariable analyses, evidence of heterogeneity in pooled estimates across studies was substantial (I^2=50%–75%) for 12 and high (I^2>75%) for 15 metabolic measures (Figures 2 and 3; Tables IVA and V in the Data Supplement). This did not seem to be accounted by sex (Figures I through IV in the Data Supplement), geographic location (Figures V and VI in the Data Supplement), or high risk of disease (Figures VII and VIII in the Data Supplement). Results were consistent for metabolites not included in the main analysis (Figures IX and X in the Data Supplement).

Causal Effects of Adiponectin on the Systemic Metabolic Profile

Characteristics of the 4 SNPs (rs6810075, rs16861209, rs17366568, and rs3774261) used in Mendelian randomization and their association with adiponectin concentration are

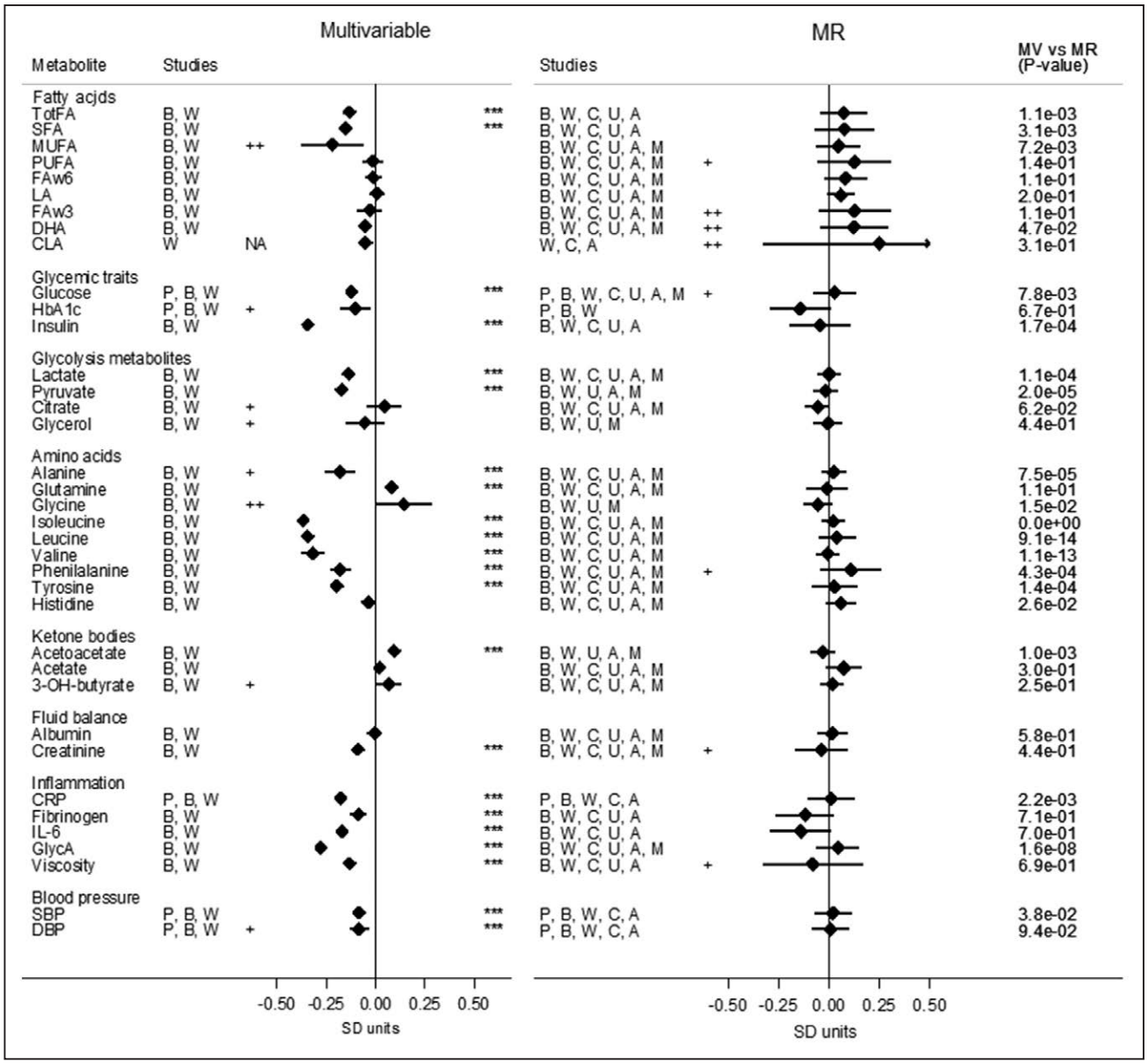

Figure 3. Association of multiple metabolic measures with blood adiponectin levels from multivariable and Mendelian randomization (MR) analysis. Values are expressed as units of standardized metabolite concentration (and 95% CI [confidence interval]) per 1 U increment of standardized log adiponectin levels. *P* values for the association between adiponectin and metabolites are indicated by *** if lower than Bonferroni-adjusted threshold (*P* value <0.0019). Heterogeneity was considered substantial if I^2=50% to 75% (+) or high if I^2>75% (++). *P* values for the comparison between multivariable and MR estimates are displayed in the column MR vs MV (*P* value). Metabolic measures were adjusted for age, sex, and, if applicable, place of recruitment (BWHHS [British Women's Heart and Health Study] and UKCTOCS [the United Kingdom Collaborative Trial of Ovarian Cancer Screening]) or principal components of genomic ancestry (PEL82 [1982 Pelotas Birth Cohort] and some studies contributing to Metabolomics consortium) and the resulting residuals were transformed to normal distribution by inverse rank-based normal transformation. A indicates the Avon Longitudinal Study of Children and Parents-Mothers' Cohort; B, BWHHS; C, the Caerphilly Prospective Study; CLA, conjugated linoleic acids; CRP, C-reactive protein; DBP, diastolic blood pressure; DHA, docosahexaenoic acid; FAw3, omega-3 fatty acid; FAw6, omega-6 fatty acid; GlycA, glycoprotein acetyls; HbA1c, glycated hemoglobin; IL-6, interleukin-6; LA, linoleic acid; M, Metabolomics consortium; MUFA, monounsaturated fatty acid; P, PEL82; PUFA, polyunsaturated fatty acids; SBP, systolic blood pressure; SFA, saturated fatty acid; TotFA, total fatty acids; U, UKCTOCS Nested Case–Control Study, and W, Whitehall II Study.

shown in Table 3. Overall, SNPs effect allele frequency was similar across studies. Two SNPs had lower allele frequency in the Metabolomics consortium (rs6810075: 51% versus 65%–69% in other studies; rs16861209: 5% versus 9%–11% in other studies), and 1 SNP had a higher frequency in PEL82 compared with other studies (rs3774261: 49% versus 38%–39% in other studies; Table 3). As expected, the selected SNPs were not associated with classical confounders overall (Table VI in the Data Supplement).

Findings from Mendelian randomization analysis were largely inconsistent with results from multivariable analysis. First, there was no evidence that adiponectin influenced HDL and VLDL traits (Figure 2). Second, genetically increased adiponectin levels were not associated with glycemic traits, free

Table 3. Characteristics of SNPs Selected for Mendelian Randomization Analysis

	SNP			
	rs6810075	rs16861209	rs17366568	rs3774261
Chr	3	3	3	3
Position*	186548565	186563114	186570453	186571559
Closest gene	*ADIPOQ*	*ADIPOQ*	*ADIPOQ-AS1, ADIPOQ*	*ADIPOQ-AS1, ADIPOQ*
EA	T	A	G	A
NEA	C	C	A	G
ADIPOGen consortium				
EAF†	0.63	0.07	0.90	0.39
β	0.11	0.31	0.25	0.11
SE	0.01	0.02	0.01	0.01
PEL82				
EAF	0.65	0.11	0.92	0.49
β	0.13	0.33	0.22	0.08
SE	0.03	0.04	0.05	0.03
R^2	0.008	0.021	0.005	0.002
BWHHS				
EAF	0.67	0.09	0.89	0.38
β	0.32	0.30	1.04	0.30
SE	0.10	0.14	0.24	0.08
R^2	0.022	0.020	0.051	0.044
WHII				
EAF	0.68	0.10	0.89	0.38
β	0.16	0.36	0.56	0.14
SE	0.04	0.05	0.08	0.03
R^2	0.008	0.027	0.025	0.010
CaPS§				
EAF	0.69	0.10	0.89	0.39
UKCTOCS§				
EAF	0.69	0.10	0.89	0.38
ALSPAC-M§				
EAF	0.66	0.09	0.93	0.38
Metabolomics consortium§				
EAF	0.51	0.05	0.88	0.36

β (and SE) refers to mean difference in standardized log adiponectin per additional SNP effect allele. ALSPAC-M indicates the Avon Longitudinal Study of Children and Parents-Mothers' Cohort; BWHHS, British Women's Heart and Health Study; CaPS, the Caerphilly Prospective Study; Chr, chromosome; EA, effect allele; EAF, effect allele frequency; NEA, noneffect allele; PEL82, 1982 Pelotas Birth Cohort; SNP, single-nucleotide polymorphism; UKCTOCS, case–control study nested in the United Kingdom Collaborative Trial of Ovarian Cancer Screening; and WHII study, Whitehall II.

*Genome Reference Consortium Human Build 37.

§For CaPS, UKCTOCS, ALSPAC-M, and the Metabolomics consortium, data on adiponectin levels were not available.

†Extracted from Dastani et al (2012).[42]

amino acids, and glycolysis-related metabolites (Figure 3). Results were less conclusive for some inflammatory markers (IL-6 and fibrinogen; Figure 3). Third, there was strong statistical evidence that associations from multivariable and Mendelian randomization analyses were inconsistent with each other (Figures 2 and 3), and the overall correlation between multivariable and Mendelian randomization estimates was low (r=0.10; Figure 4). Finally, in the Mendelian randomization analysis, adiponectin was not associated with any of the metabolic measures at either P <0.05 or P <0.0019.

In the Mendelian randomization analyses, evidence of heterogeneity in pooled estimates across studies was substantial (I^2=50%–75%) for 14 and high (I^2>75%) for 3 metabolic measures, suggesting lower heterogeneity in models from genetic analysis than from the multivariable analyses (Figures 2 and 3; Tables IVB and V in the Data Supplement). This did not seem to be driven by sex differences (Figures I through IV in the Data Supplement), geographic location/ethnicity (Figures V and VI in the Data Supplement), or high risk of disease (Figures VII and VIII in the Data Supplement). Results were consistent with no association between adiponectin and metabolites not included in the main analysis (Figures IX and X in the Data Supplement).

Discussion

In ≤5909 adults, we found using multivariable regression analyses that circulating adiponectin was associated with a pattern of systemic metabolites levels associated with good health. Higher blood adiponectin concentration was associated with higher HDL lipids and lower VLDL lipids, glycemia, and branched-chain amino acids levels. However, when we used genetic variants in the vicinity of adiponectin-encoding gene to test the causal effect of adiponectin on systemic metabolic profiles among ≤37 545 adults, we found little evidence that the associations were causal.

Genetic association studies indicate that genetic variants associated with circulating adiponectin (in loci other than *ADIPOQ*) are also associated with cardiometabolic outcomes, such as type 2 diabetes mellitus[42] and coronary heart disease[41]; however, this is likely to be reflecting a pleiotropic effect of these variants. Our findings and previous Mendelian randomization studies[19,22] suggest that the association between circulating adiponectin and metabolic biomarkers and cardiometabolic diseases is likely to be explained by shared factors (confounding) rather than by a direct role of adiponectin on metabolism and downstream cardiometabolic disease. These results are in contrast to findings from animal models pointing to insulin-sensitizing and antiatherogenic actions of adiponectin.[1]

Circulating adiponectin is known to be substantially reduced among obese individuals, particularly in the presence of central fat accumulation.[45] A recent Mendelian randomization study examining the causal metabolic effects of body mass index demonstrated that lower body mass index was related to favorable lipoprotein subclass profile and lower concentration of branched-chain amino acids, inflammatory markers, and insulin,[34] which is remarkably similar to our results from the conventional multivariable analysis. In addition, numerous studies have shown that adiponectin production is suppressed by insulin action in humans, which seems to be at least partly attributed to regulation at the transcriptional level.[46] As

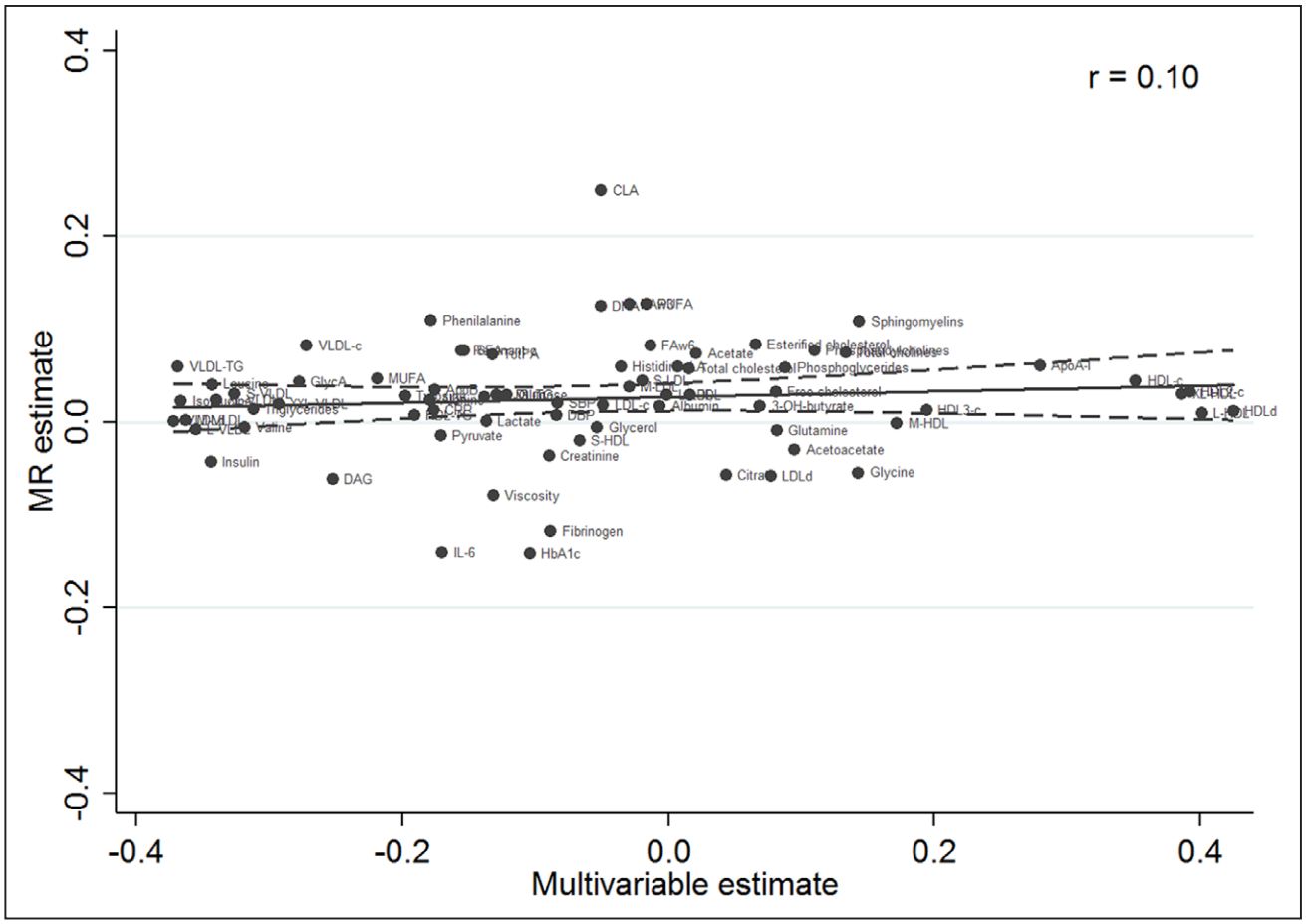

Figure 4. Correlation between estimates from multivariable regression and Mendelian randomization (MR). Apo indicates apolipoprotein; CLA, conjugated linoleic acids, CRP, C-reactive protein; DAG, diglycerides; DBP, diastolic blood pressure; DHA, docosahexaenoic acid; FAw3, omega-3 fatty acid; FAw6, omega-6 fatty acid; GlycA, glycoprotein acetyls; HbA1c, glycated hemoglobin; HDL, high-density lipoprotein; HDL-C, HDL cholesterol; HDLd, HDL particle mean diameter; IDL, intermediate-density lipoprotein; IDL-C, IDL cholesterol; IL-6, interleukin-6; L-HDL, large HDL; L-LDL, large LDL; L-VLDL, large VLDL; LA, linoleic acid; LDL, low-density lipoprotein; LDL-C, LDL cholesterol; LDLd, LDL particle mean diameter M-HDL, medium HDL; M-LDL, medium LDL; M-VLDL, medium VLDL; MUFA, monounsaturated fatty acid; *r*, Pearson correlation coefficient; S-HDL, small HDL; S-LDL, small LDL; S-VLDL, small VLDL; SBP, systolic blood pressure; SFA, saturated fatty acid; TG, triglycerides; VLDL, very-low-density lipoprotein; VLDL-C, VLDL cholesterol; VLDLd, VLDL particle mean diameter; XL-HDL, very large HDL; XL-VLDL, very large VLDL; XS-VLDL, very small VLDL; and XXL-VLDL, extremely large VLDL.

an example, elevated circulating adiponectin is found in contexts of both primary deficiency of insulin (type 1 diabetes mellitus)[47] and global insulin resistance because of genetic or acquired defects in the insulin receptor.[48] Genetic predisposition to insulin resistance and central fat accumulation[45,49] is related to lower circulating adiponectin. Evidence from animal models has raised the possibility of a bidirectional relationship between adiponectin and insulin concentration.[50] Early Mendelian randomization studies did indicate that adiponectin could mitigate insulin resistance[20,21]; however, these results could not be replicated in a larger Mendelian randomization study,[19] as well as in our study presented here. The well-known metabolic effects of adiposity and insulin on circulating adiponectin concentration reinforce that the clustering of adiponectin and several traditional and novel biomarkers is likely to result from confounding because of increasing adiposity and disruption of insulin action.

Strengths of our study include detailed metabolic profile in several longitudinal studies, which enabled us to characterize the metabolic profile of high adiponectin concentration beyond traditional biomarkers, as well as the use of Mendelian randomization to disentangle the causal effect of adiponectin on the metabolism. Mendelian randomization analysis can reliably test for the presence of a causal relation under the 3 assumptions of an instrumental variable that the genetic variants (1) are robustly associated with the risk factor of interest (adiponectin), (2) should only affect the outcome (metabolites) through the exposure, and (3) are not associated with exposure–outcome confounders.[51] To ensure that the instrumental variable assumptions were met, or were at least plausible, we only used SNPs strongly and specifically (within *ADIPOQ* gene) related to adiponectin concentration as instrumental variables and we adjusted for population structure in models using data from PEL82 to avoid confounding by population stratification. One of the limitations of our study was the limited power in subgroup analyses including only individual-level data (sex- and risk-stratified analyses), which limited our investigation of potential sources of heterogeneity. Another limitation was the absence of data on high–molecular weight adiponectin, which is believed to account for most of the adiponectin biological effects in experimental settings. However, most human

(and many animal model) studies have not used high–molecular weight adiponectin, and we found the same multivariable observational associations as in previous studies. Also, it should be emphasized that SNPs in *ADIPOQ* gene are associated with both total and high–molecular weight adiponectin,[52–54] including SNPs we used in our analysis (eg, rs3774261)[52] or others in high linkage disequilibrium with these (eg, rs16861209 is highly correlated with rs17300539 – R^2 >0.8).[53,54]

Overall, our findings suggest that low circulating adiponectin is likely to reflect adipocyte dysfunction and that altered total blood adiponectin concentration is an epiphenomenon in the context of metabolic disease, rather than a key determinant. Therefore, interventions targeting manipulation of adiponectin concentration are unlikely to result in therapeutic benefits for tackling cardiometabolic diseases. Our results highlight the potential of Mendelian randomization analysis and high-throughput metabolomics profiling to yield important insights to advance our understanding in the pathophysiology of common complex diseases and to inform which targets are best bets for taking forward into drug development, given that drug target validation is a key obstacle underlying the unsustainably high rate of drug development failure. Although our and other studies suggest that adiponectin is not a valuable target for developing drugs aimed at preventing cardiometabolic diseases, it may nonetheless be a valuable biomarker for predicting these diseases given the wide-ranging associations shown here. The associations we have found would need to be replicated in additional independent studies before testing their ability to predict disease outcomes.

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Disclosures

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CLINICAL PERSPECTIVE

Adiponectin, a protein produced by adipose cells, has insulin-sensitizing, anti-inflammatory, antiatherogenic, and cardiomyocyte-protective properties in animal models. In prospective studies in humans, higher circulating adiponectin is associated with lower risk of type 2 diabetes mellitus, hepatic dysfunction, and metabolic syndrome. However, it is not clear whether adiponectin is protective against these metabolic disorders or whether these associations are just reflecting reverse causality (where disease status could alter adiponectin concentration) or residual confounding (where adiponectin could be a marker of another causal factor, such as adiposity or insulin resistance). We used Mendelian randomization to clarify whether circulating adiponectin is causally related to the metabolic profile of ≤37 545 adults. Four common genetic variants nearby the gene encoding adiponectin (*ADIPOQ*) were used as instruments to test the effect of circulating adiponectin on 74 metabolic measures selected to broadly represent the systemic metabolite profile, including lipoprotein subclasses, fatty acids, glycemic traits, free amino acids, inflammatory markers, and blood pressure. Overall, our findings do not support a direct role of circulating adiponectin on the systemic metabolic profile in humans and indicate that the clustering of adiponectin and several traditional and novel biomarkers is likely to result from confounding or reverse causality. Therefore, interventions targeting manipulation of adiponectin concentration are unlikely to result in therapeutic benefits for tackling metabolic diseases.

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Metabolic Profiling of Adiponectin Levels in Adults: Mendelian Randomization Analysis

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SUPPLEMENTAL MATERIAL

SUPPLEMENTARY METHODS

Nuclear magnetic resonance (NMR) spectroscopy platform

Over 150 quantified metabolomic measures were obtained per sample of EDTA-plasma, using a 1D proton (^{1}H) NMR spectroscopy-based platform described previously (1-4). Briefly, the serum samples were stored in a freezer at -80^{o}C. The frozen samples were first slowly thawed in a refrigerator (+4^{o}C) overnight prior to metabolomics profiling. 260 µL plasma and 260 µL sodium phosphate buffer (75 mM Na2HPO4, 0.08% sodium 3-(trimethylsilyl)propionate-2,2,3,3-d4, 0.04% sodium azide in 80%/20% H20/D2O, pH 7.4) were mixed and transferred to NMR tubes using an 8-channel, Varispan Janus liquid handling robot (PerkinElmer). NMR spectra were acquired using a Bruker Avance III HD 500MHz spectrometer with a room temperature 5mm, inverse triple resonance TXI probe and a Bruker Avance III HD 600MHz spectrometer equipped with a nitrogen-cooled triple resonance probe (CryoProbe Prodigy TCI). Both spectrometers were equipped with SampleJet auto-samplers with cooled (6°C) sample storage. Spectra were acquired using standardized parameters using three NMR experiments or 'molecular windows' to characterize lipoproteins, low molecular weight metabolites and lipids. Lipid spectra were acquired after a standardised lipid extraction procedure performed on each sample using a VIAFLO 96 channel electronic pipette (Integra Biosciences). Data pre-processing and quantification were as previously described (1-4). The NMR spectra were analysed for absolute quantification using regression models (5). The 14 lipoprotein subclass sizes were defined as follows: very low density lipoprotein (VLDL) is subdivided into six subclasses, the largest being extremely large VLDL with particle diameters from 75 nm upwards and a possible contribution of chylomicrons, and five remaining VLDL subclasses (average particle diameters of 64.0 nm, 53.6 nm, 44.5 nm, 36.8 nm, and 31.3 nm); Intermediate density lipoprotein (IDL) (28.6 nm), three low density lipoprotein (LDL) subclasses (25.5 nm, 23.0 nm, and 18.7 nm), and four high density lipoprotein (HDL) subclasses (14.3 nm, 12.1 nm, 10.9 nm, and 8.7 nm). The mean sizes for VLDL, LDL and HDL particles were calculated by weighting the corresponding subclass diameters with their particle concentrations (4). There is a high analytical consistency, in epidemiological settings, between metabolic measures quantified by the NMR metabolomics platform and the concentrations obtained from routine clinical chemistry (6), and other analytical methods, such as gas chromatography (6, 7) and enzymatic

method (6), with correlations >0.9. In addition, the consistency of biomarker associations with disease incidence for metabolic traits quantified by NMR and two widely used mass spectroscopy platforms has been demonstrated (6, 7).

Selection of genetic variants

The SNPs used for the Mendelian randomization analysis were selected from 145 SNPs with good evidence ($p < 5*10^{-8}$) for association with blood adiponectin concentration in the European ancestry GWAS meta-analysis from the ADIPOGen consortium (8). ADIPOGen participating studies tested for the additive genetic association of SNPs with natural log transformed adiponectin levels, while adjusting for age, sex, BMI, principal components of population stratification and study site (where appropriate), and for family structure in cohorts with family members. Independent SNPs within the *ADIPOQ* locus (± 50 kb) have been previously selected by Dastani et al (2013) (9) by linkage disequilibrium (LD) prunning of the genome-wide significant SNPs, retaining SNPs that explained most variance in adiponectin concentration in each LD block (LD threshold: $R^2 < 0.05$ in HapMap CEU population (Utah residents with Northern and Western European ancestry)).

The discovery sample from ADIPOGen GWAS was largely independent from the sample used to estimate the association between SNP and metabolites in our study. We estimated that, depending on the metabolite, between zero and 26% of participants included in the analysis of SNP-metabolites association would have been included in the discovery ADIPOGen GWAS.

Mendelian randomization analyses

The two-sample Mendelian randomization estimates and respective standard errors were obtained by meta-analyzing SNP-specific Wald ratios (i.e. ratio between SNP-outcome and SNP-exposure association) with the following formulas:

$$\hat{\beta} = \frac{\sum_{k=1}^{K} X_k Y_k \, \sigma_{yk}^{-2}}{\sum_{k=1}^{K} X_k^2 \sigma_{yk}^{-2}} \qquad SE_{\hat{\beta}} = \sqrt{\frac{1}{\sum_{k=1}^{K} X_k^2 \sigma_{yk}^{-2}}}$$

Where X_k is the mean change in standardized log adiponectin units per additional effect allele of SNP k and Y_k is the mean change in standardized units of metabolic measures per additional effect allele of SNP k with standard error σ_{Yk}. To increase precision and avoid bias due to statistical overfitting, estimates for X_k were obtained from ADIPOGen consortium dataset (8). Prior to analysis, estimates from ADIPOGen consortium were standardized (converted from log adiponectin to standardized log adiponectin units) using individual level data from PEL82 with a similar adiponectin distribution (adiponectin concentration in ADIPOGen consortium: mean = 9.8 µg/ml (standard deviation = 5.6); adiponectin concentration in 1982 Pelotas Birth Cohort: mean = 9.3 µg/ml (standard deviation = 5.7)). Estimates for Y_k were derived from each study using linear regression models considering an additive model for SNP alleles.

Comparison between multivariable and Mendelian randomization analyses

Results from conventional multivariable and Mendelian randomization analyses were compared using the Z-test:

$$Z = (\beta_{mva} - \beta_{MR})/\sqrt{(SE_{mva}^2 + SE_{MR}^2)}$$

Where β_{mv} represents estimates from conventional multivariable analysis (with respective standard error, SE_{mv}) and β_{MR} represents estimates from Mendelian randomization analysis (with respective standard error, SE_{MR}).

Proportion of variance in adiponectin concentration explained by genetic instruments

In order to estimate the strength of our genetic instruments, we estimated the phenotypic variance explained by a given SNP (R^2) for adiponectin concentration. We used ADIPOGen summary data to approximate R^2 for a given SNP based on the effect estimate for its association with the trait of interest (beta or $\hat{\beta}$), respective standard error ($se(\hat{\beta})$), minor allele frequency (MAF), and sample size (N). The following formula was used as previously described by Shim et al., 2015 (10):

$$R^2 \cong \frac{2\hat{\beta}^2 MAF(1-MAF)}{2\hat{\beta}^2 MAF(1-MAF) + (se(\hat{\beta}))^2 2NMAF(1-MAF)}$$

The phenotypic variance explained by the composite genetic instrument (combining all SNPs) was estimated by the sum of SNP-specific R^2 as shown below:

SNPs used as instrumental variables for adiponectin concentration in Mendelian randomization analysis and association with adiponectin concentration

rs ID	Chr	EA	NEA	EAF	R^2	N
rs6810075	3	T	C	0.63	0.0066	29140
rs16861209	3	A	C	0.01	0.0125	29199
rs17366568	3	G	A	0.91	0.0125	24865
rs3774261	3	A	G	0.60	0.0080	29081
Combined instrument	N/A	N/A	N/A	N/A	0.0396	N/A

Chr: chromosome; EA: effect allele (trait-increasing allele); NEA: non-effect allele; R^2: proportion of phenotypic variance explained by SNP; Beta: increase in standardized log adiponectin concentration per EA; SE: standard error; N: sample size; N/A: not applicable.

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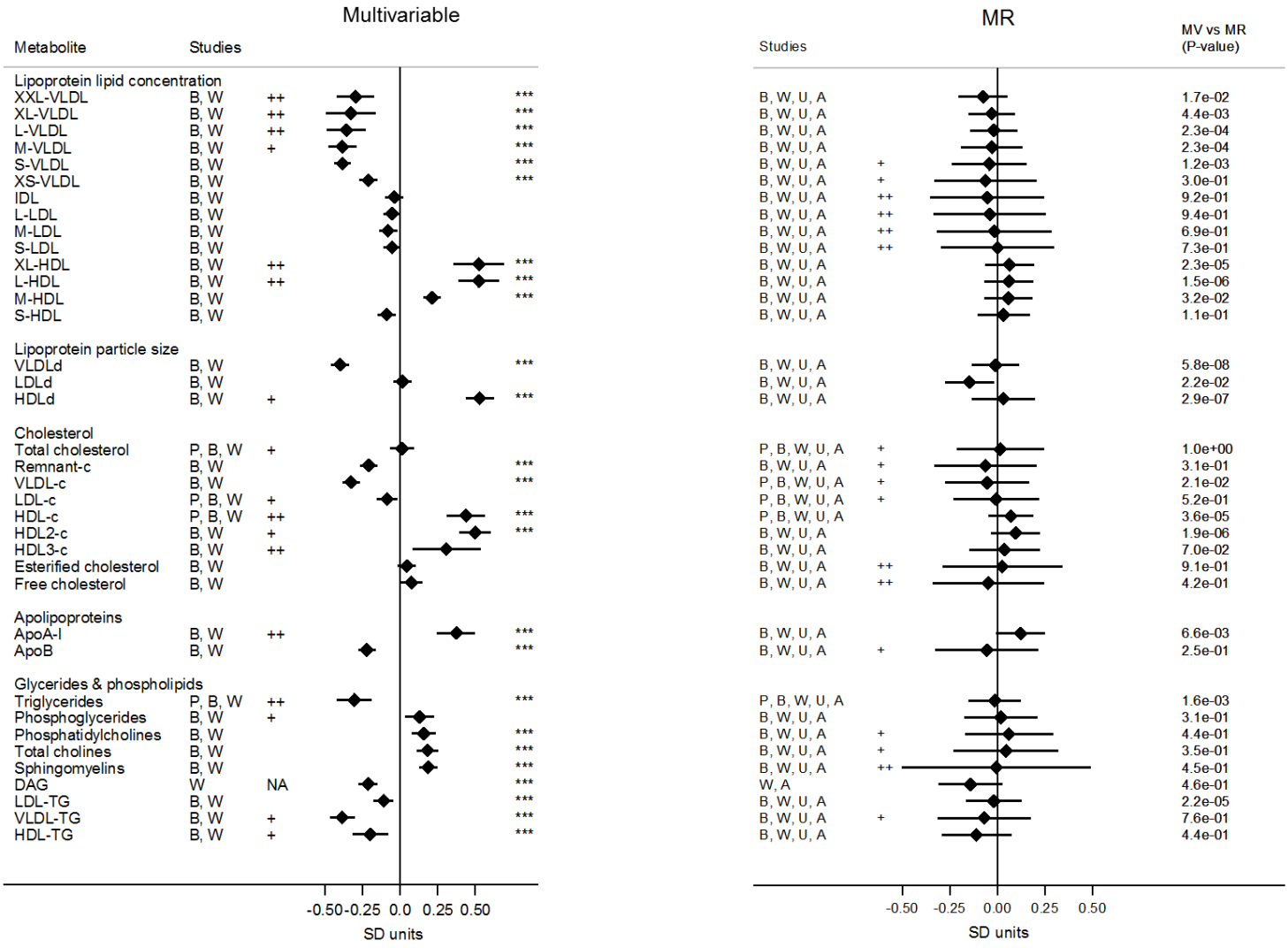
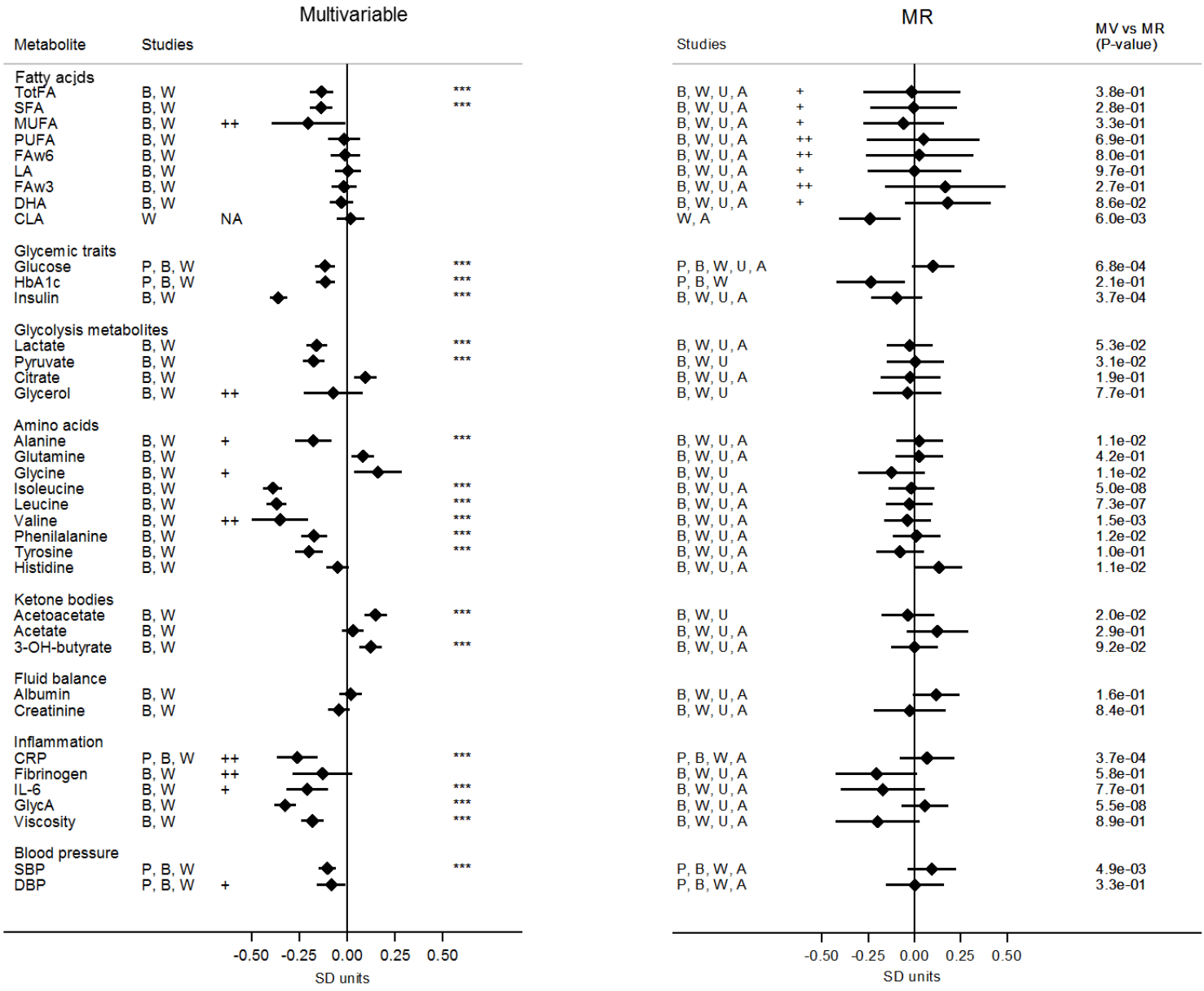


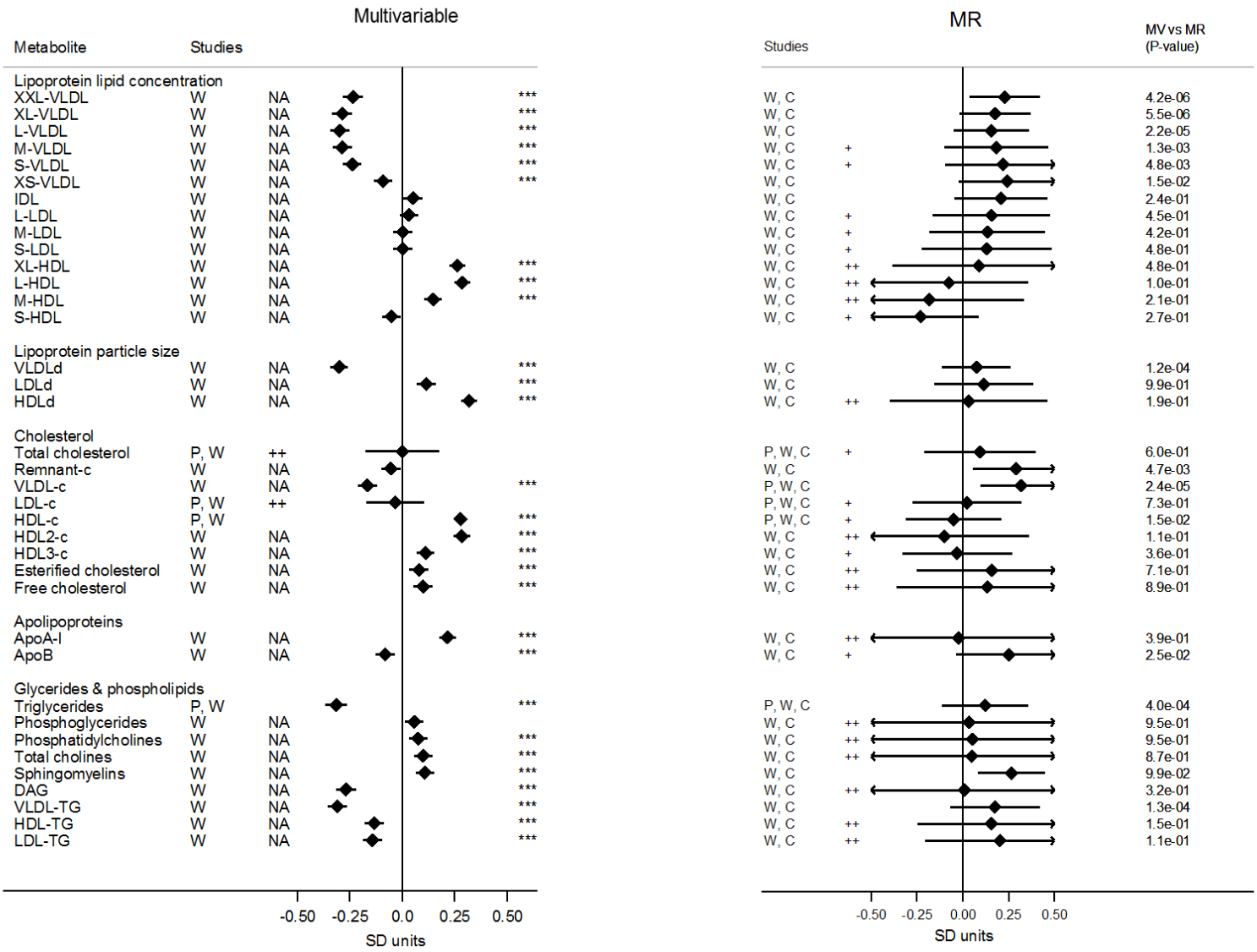
Supplementary figure 1. Association of lipoprotein traits with blood adiponectin levels from observational and Mendelian randomization (MR) analysis among women.

Values are expressed as units of standardized log metabolite concentration (and 95% CI) per 1 unit increment of standardized log adiponectin levels. P-values for the association between adiponectin and metabolites are indicated by three asterisks ("***") if lower than Bonferroni-adjusted threshold (P-value < 0.0019). Heterogeneity was considered substantial if I^2 = 50-75% ("+") or very high if I^2 > 75% ("++"). P-values for the comparison between multivariable and Mendelian randomization estimates are displayed in the column "MR vs MV (P-value)". Metabolic measures were adjusted for age, sex, and, if applicable, place of recruitment (BWHHS and UKCTOCS) or principal components of genomic ancestry (PEL82 and some studies contributing to Metabolomics consortium) and the resulting residuals were transformed to normal distribution by inverse rank-based normal transformation. XXL: extremely large, XL: very large, L: large, M: medium, S: small, XS: very small, VLDL: very low-density lipoprotein, LDL: low-density lipoprotein, IDL: intermediate-density lipoprotein, HDL: high-density lipoprotein, c: cholesterol, DAG: diglycerides, TG: triglycerides, P: 1982 Pelotas Birth Cohort, B: British Women Heart and Health Study, W: Whitehall II Study, U: UKCTOCS nested case-control study, , A: The Avon Longitudinal Study of Children and Parents – mothers' cohort, SD units: standard deviation units, CI: confidence interval.



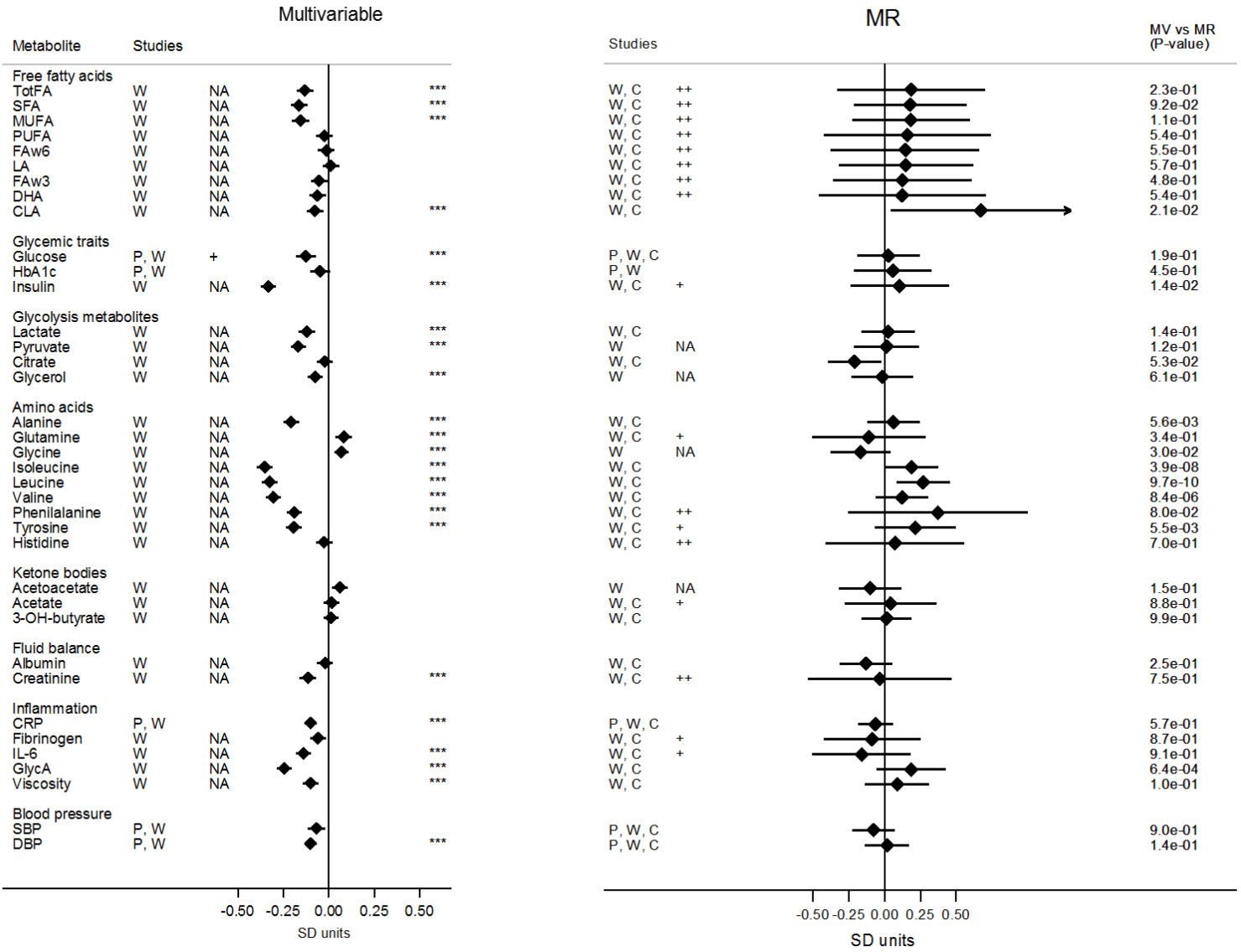
Supplementary figure 2. Association of multiple metabolic measures with blood adiponectin levels from observational and Mendelian randomization analysis among women.

Values are expressed as units of standardized log metabolite concentration (and 95% CI) per 1 unit increment of standardized log adiponectin levels. P-values for the association between adiponectin and metabolites are indicated by three asterisks ("***") if lower than Bonferroni-adjusted threshold (P-value < 0.0019). Heterogeneity was considered substantial if I^2 = 50-75% ("+") or very high if I^2 > 75% ("++"). P-values for the comparison between multivariable and Mendelian randomization estimates are displayed in the column "MR vs MV (P-value)". Metabolic measures were adjusted for age, sex, and, if applicable, place of recruitment (BWHHS and UKCTOCS) or principal components of genomic ancestry (PEL82 and some studies contributing to Metabolomics consortium) and the resulting residuals were transformed to normal distribution by inverse rank-based normal transformation. TotFA: total fatty acids, SFA: saturated fatty acid, MUFA: monounsaturated fatty acid, PUFA: polyunsaturated fatty acids, FAw6: omega-6 fatty acid, LA: linoleic acid, FAw3: omega-3 fatty acid, DHA: docosaexaenoic acid, CLA: conjugated linoleic acids, HbA1c: glycated haemoglobin, CRP: c-reactive protein, IL-6: interleukin-6, GlycA: glycoprotein acetyls, SBP: systolic blood pressure, DBP: diastolic blood pressure, P: 1982 Pelotas Birth Cohort, B: British Women Heart and Health Study, W: Whitehall II Study, U: UKCTOCS nested case-control study, A: The Avon Longitudinal Study of Children and Parents – mothers' cohort, SD units: standard deviation units, CI: confidence interval.



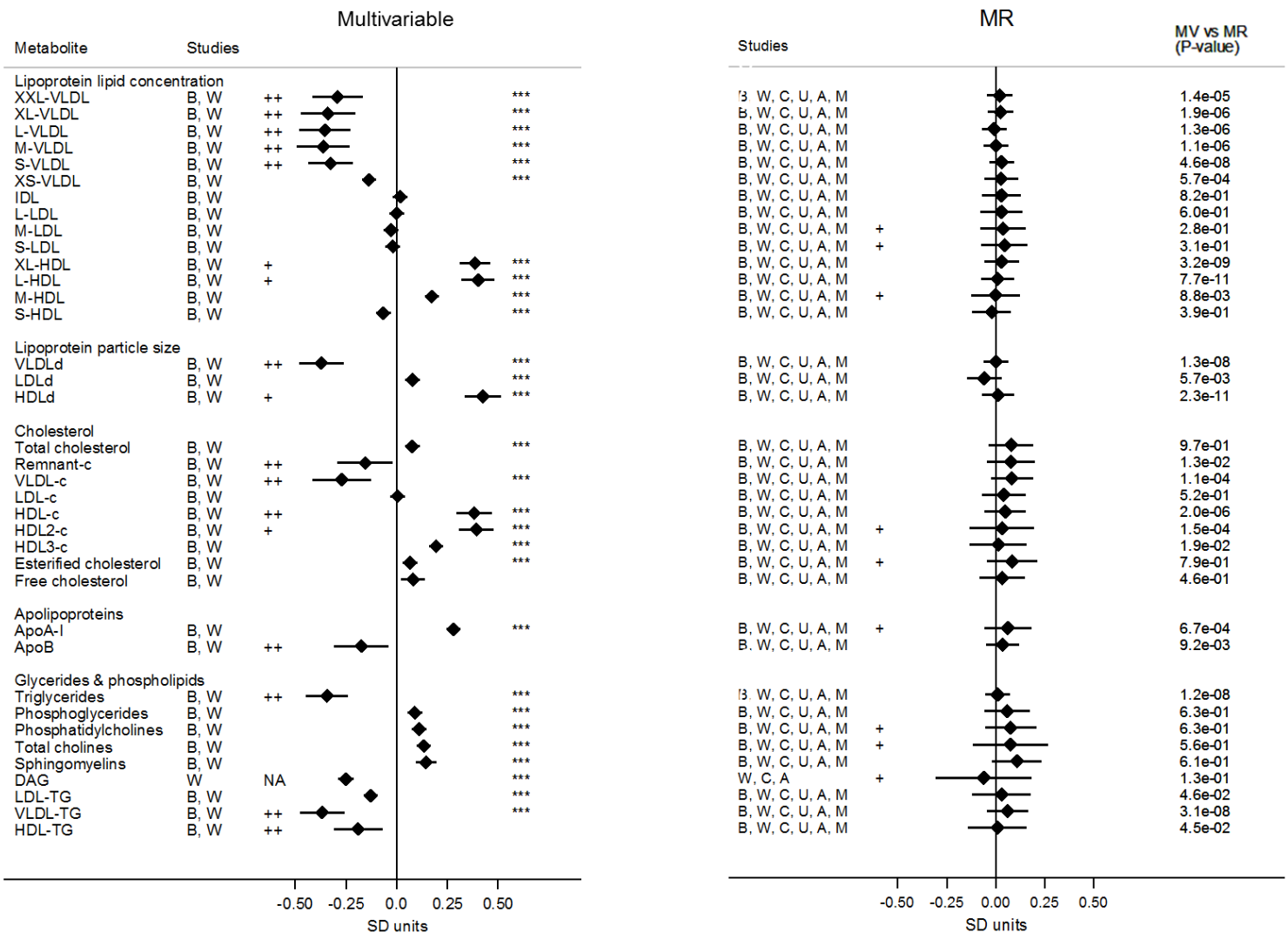
Supplementary figure 3. Association of lipoprotein traits with blood adiponectin levels from observational and Mendelian randomization (MR) analysis among men.

Values are expressed as units of standardized log metabolite concentration (and 95% CI) per 1 unit increment of standardized log adiponectin levels. P-values for the association between adiponectin and metabolites are indicated by three asterisks ("***") if lower than Bonferroni-adjusted threshold (P-value < 0.0019). Heterogeneity was considered substantial if I^2 = 50-75% ("+"), very high if I^2 > 75% ("++") or not applicable ("NA") when only one study contributed to the estimate. P-values for the comparison between multivariable and Mendelian randomization estimates are displayed in the column "MR vs MV (P-value)". Metabolic measures were adjusted for age, sex, and, if applicable, place of recruitment (BWHHS and UKCTOCS) or principal components of genomic ancestry (PEL82 and some studies contributing to Metabolomics consortium) and the resulting residuals were transformed to normal distribution by inverse rank-based normal transformation. XXL: extremely large, XL: very large, L: large, M: medium, S: small, XS: very small, VLDL: very low-density lipoprotein, LDL: low-density lipoprotein, IDL: intermediate-density lipoprotein, HDL: high-density lipoprotein, c: cholesterol, DAG: diglycerides, TG: triglycerides, P: 1982 Pelotas Birth Cohort, W: Whitehall II Study, C: The Caerphilly Prospective Study, SD units: standard deviation units, CI: confidence interval.



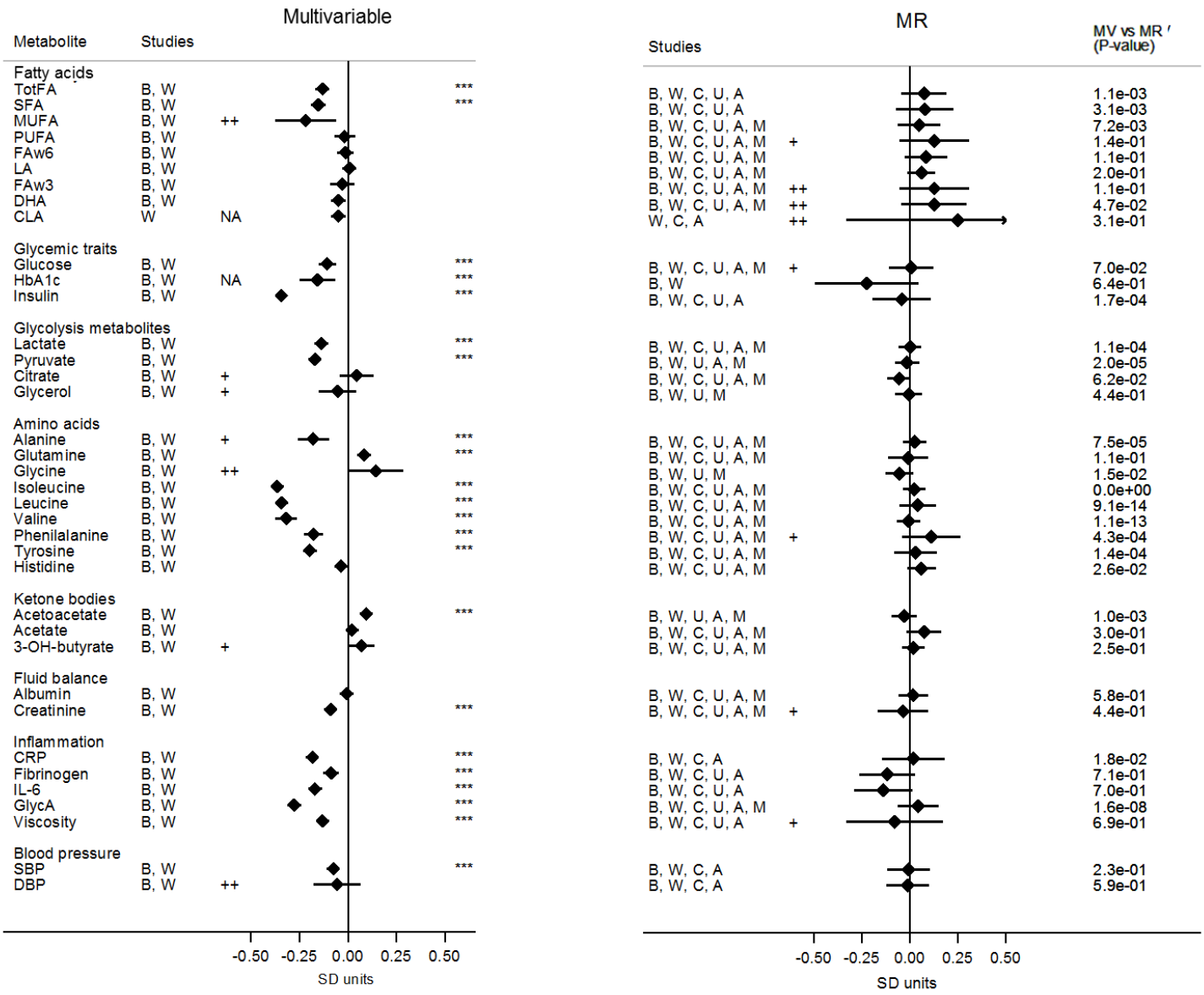
Supplementary figure 4. Association of multiple metabolic measures with blood adiponectin levels from observational and Mendelian randomization analysis among men.

Values are expressed as units of standardized log metabolite concentration (and 95% CI) per 1 unit increment of standardized log adiponectin levels. P-values for the association between adiponectin and metabolites are indicated by three asterisks ("***") if lower than Bonferroni-adjusted threshold (P-value < 0.0019). Heterogeneity was considered substantial if I^2 = 50-75% ("+") or very high if I^2 > 75% ("++") or not applicable ("NA") when only one study contributed to the estimate. P-values for the comparison between multivariable and Mendelian randomization estimates are displayed in the column "MR vs MV (P-value)". Metabolic measures were adjusted for age, sex, and, if applicable, place of recruitment (BWHHS and UKCTOCS) or principal components of genomic ancestry (PEL82 and some studies contributing to Metabolomics consortium) and the resulting residuals were transformed to normal distribution by inverse rank-based normal transformation. TotFA: total fatty acids, SFA: saturated fatty acid, MUFA: monounsaturated fatty acid, PUFA: polyunsaturated fatty acids, FAw6: omega-6 fatty acid, LA: linoleic acid, FAw3: omega-3 fatty acid, DHA: docosaexaenoic acid, CLA: conjugated linoleic acids, HbA1c: glycated haemoglobin, CRP: c-reactive protein, IL-6: interleukin-6, GlycA: glycoprotein acetyls, SBP: systolic blood pressure, DBP: diastolic blood pressure, P: 1982 Pelotas Birth Cohort, W: Whitehall II Study, C: The Caerphilly Prospective Study, SD units: standard deviation units, CI: confidence interval.



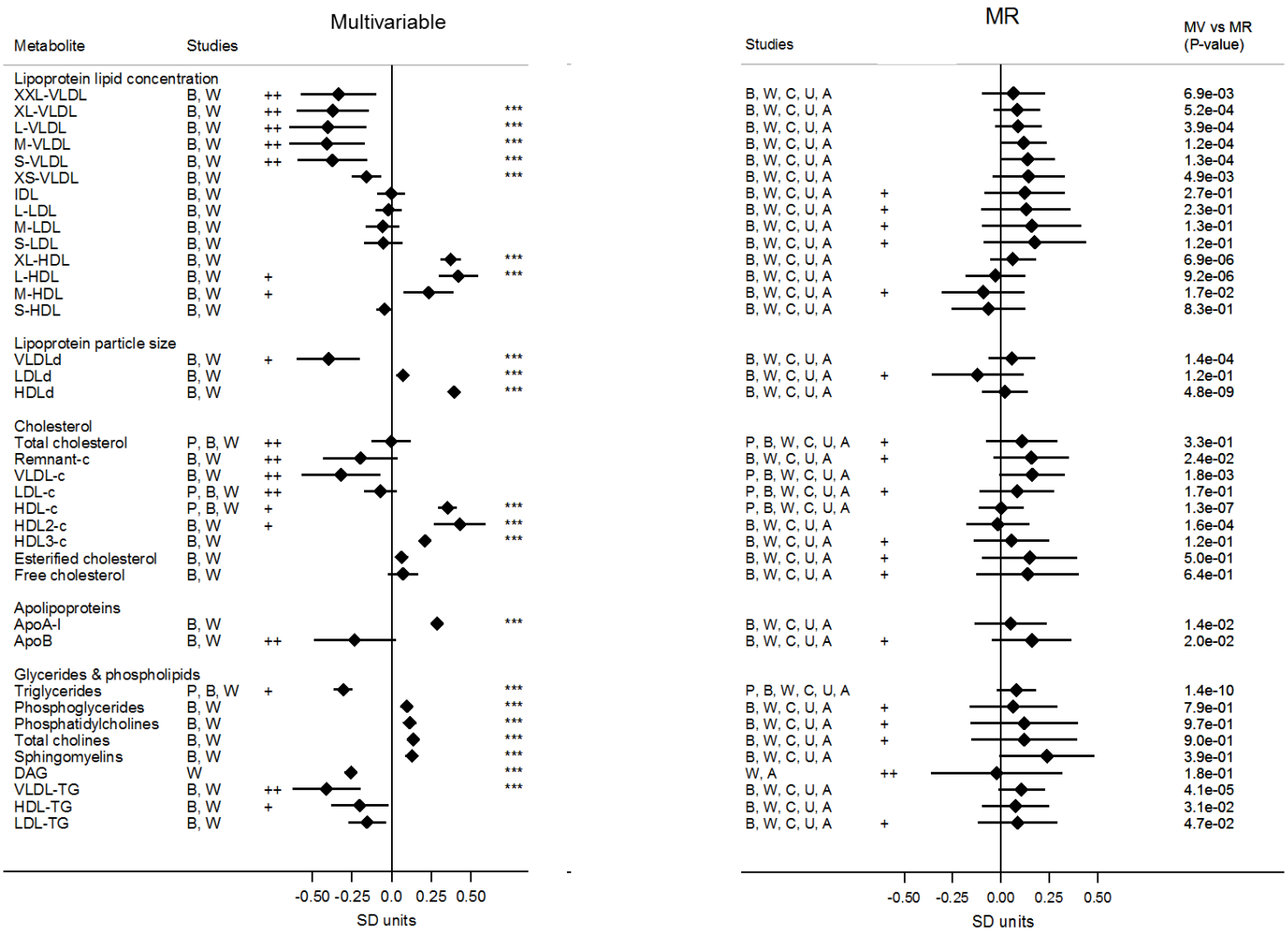
Supplementary figure 5. Association of lipoprotein traits with blood adiponectin levels from observational and Mendelian randomization (MR) analysis restricted to individuals of European ancestry.

Values are expressed as units of standardized log metabolite concentration (and 95% CI) per 1 unit increment of standardized log adiponectin levels. P-values for the association between adiponectin and metabolites are indicated by three asterisks ("***") if lower than Bonferroni-adjusted threshold (P-value < 0.0019). Heterogeneity was considered substantial if I^2 = 50-75% ("+") or very high if I^2 > 75% ("++"). P-values for the comparison between multivariable and Mendelian randomization estimates are displayed in the column "MR vs MV (P-value)". Metabolic measures were adjusted for age, sex, and, if applicable, place of recruitment (BWHHS and UKCTOCS) or principal components of genomic ancestry (PEL82 and some studies contributing to Metabolomics consortium) and the resulting residuals were transformed to normal distribution by inverse rank-based normal transformation. XXL: extremely large, XL: very large, L: large, M: medium, S: small, XS: very small, VLDL: very low-density lipoprotein, LDL: low-density lipoprotein, IDL: intermediate-density lipoprotein, HDL: high-density lipoprotein, c: cholesterol, DAG: diglycerides, TG: triglycerides, P: 1982 Pelotas Birth Cohort, B: British Women Heart and Health Study, W: Whitehall II Study, U: UKCTOCS nested case-control study, , A: The Avon Longitudinal Study of Children and Parents – mothers' cohort, M: Metabolomics consortium, SD units: standard deviation units, CI: confidence interval.



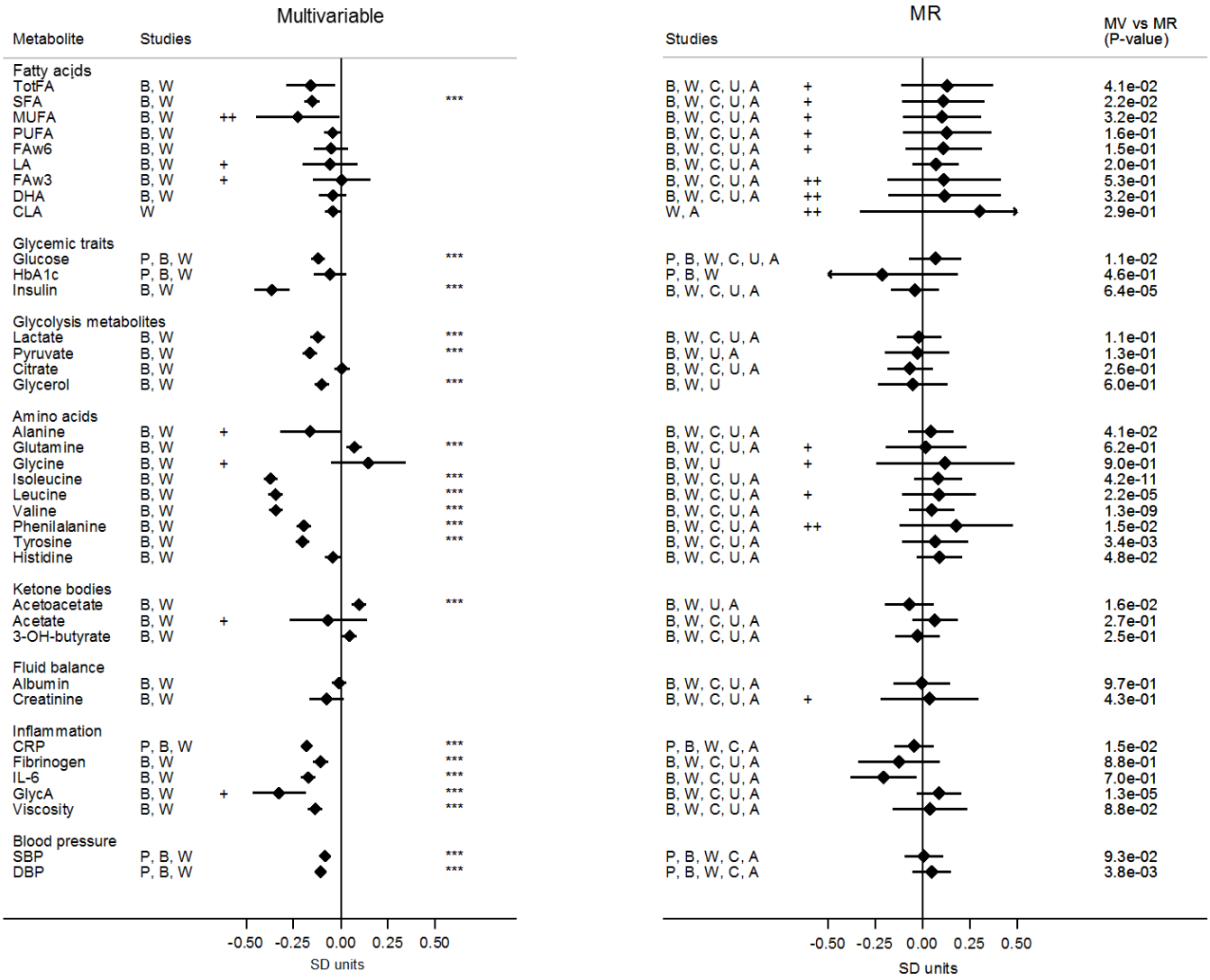
Supplementary figure 6. Association of multiple metabolic measures with blood adiponectin levels from observational and Mendelian randomization analysis restricted to individuals of European ancestry.

Values are expressed as units of standardized log metabolite concentration (and 95% CI) per 1 unit increment of standardized log adiponectin levels. P-values for the association between adiponectin and metabolites are indicated by three asterisks ("***") if lower than Bonferroni-adjusted threshold (P-value < 0.0019). Heterogeneity was considered substantial if I^2 = 50-75% ("+") or very high if I^2 > 75% ("++"). P-values for the comparison between multivariable and Mendelian randomization estimates are displayed in the column "MR vs MV (P-value)". Metabolic measures were adjusted for age, sex, and, if applicable, place of recruitment (BWHHS and UKCTOCS) or principal components of genomic ancestry (PEL82 and some studies contributing to Metabolomics consortium) and the resulting residuals were transformed to normal distribution by inverse rank-based normal transformation. TotFA: total fatty acids, SFA: saturated fatty acid, MUFA: monounsaturated fatty acid, PUFA: polyunsaturated fatty acids, FAw6: omega-6 fatty acid, LA: linoleic acid, FAw3: omega-3 fatty acid, DHA: docosaexaenoic acid, CLA: conjugated linoleic acids, HbA1c: glycated haemoglobin, CRP: c-reactive protein, IL-6: interleukin-6, GlycA: glycoprotein acetyls, SBP: systolic blood pressure, DBP: diastolic blood pressure, P: 1982 Pelotas Birth Cohort, B: British Women Heart and Health Study, W: Whitehall II Study, U: UKCTOCS nested case-control study, A: The Avon Longitudinal Study of Children and Parents – mothers' cohort, M: Metabolomics consortium, SD units: standard deviation units, CI: confidence interval.



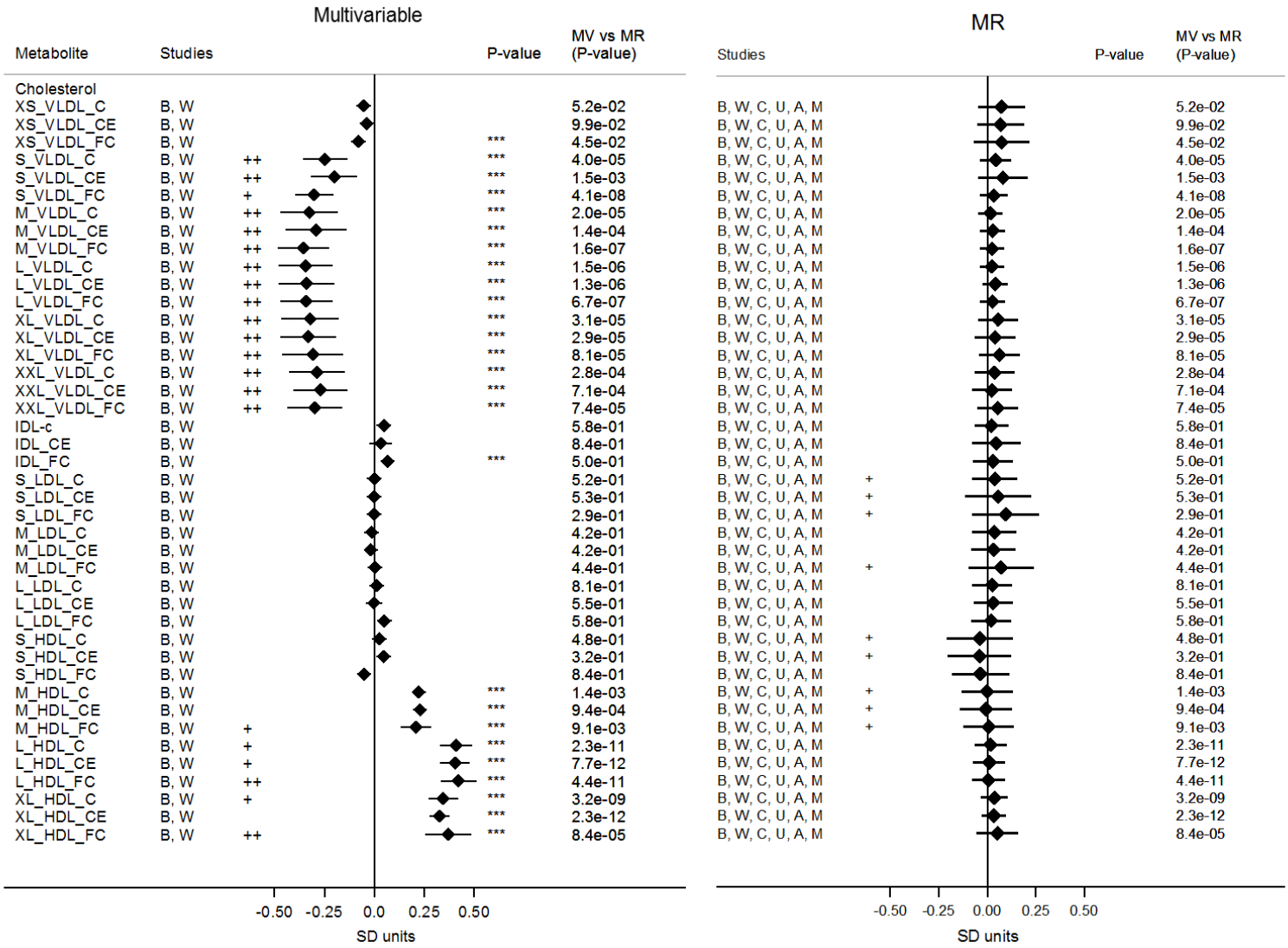
Supplementary figure 7. Association of lipoprotein traits with blood adiponectin levels from observational and Mendelian randomization (MR) analysis among younger individuals (< 65 years old) free from cardiovascular disease.

Values are expressed as units of standardized log metabolite concentration (and 95% CI) per 1 unit increment of standardized log adiponectin levels. P-values for the association between adiponectin and metabolites are indicated by three asterisks ("***") if lower than Bonferroni-adjusted threshold (P-value < 0.0019). Heterogeneity was considered substantial if I^2 = 50-75% ("+") or very high if I^2 > 75% ("++"). P-values for the comparison between multivariable and Mendelian randomization estimates are displayed in the column "MR vs MV (P-value)". Metabolic measures were adjusted for age, sex, and, if applicable, place of recruitment (BWHHS and UKCTOCS) or principal components of genomic ancestry (PEL82 and some studies contributing to Metabolomics consortium) and the resulting residuals were transformed to normal distribution by inverse rank-based normal transformation. XXL: extremely large, XL: very large, L: large, M: medium, S: small, XS: very small, VLDL: very low-density lipoprotein, LDL: low-density lipoprotein, IDL: intermediate-density lipoprotein, HDL: high-density lipoprotein, c: cholesterol, DAG: diglycerides, TG: triglycerides, P: 1982 Pelotas Birth Cohort, B: British Women Heart and Health Study, W: Whitehall II Study, U: UKCTOCS nested case-control study, A: The Avon Longitudinal Study of Children and Parents – mothers' cohort, SD units: standard deviation units, CI: confidence interval.



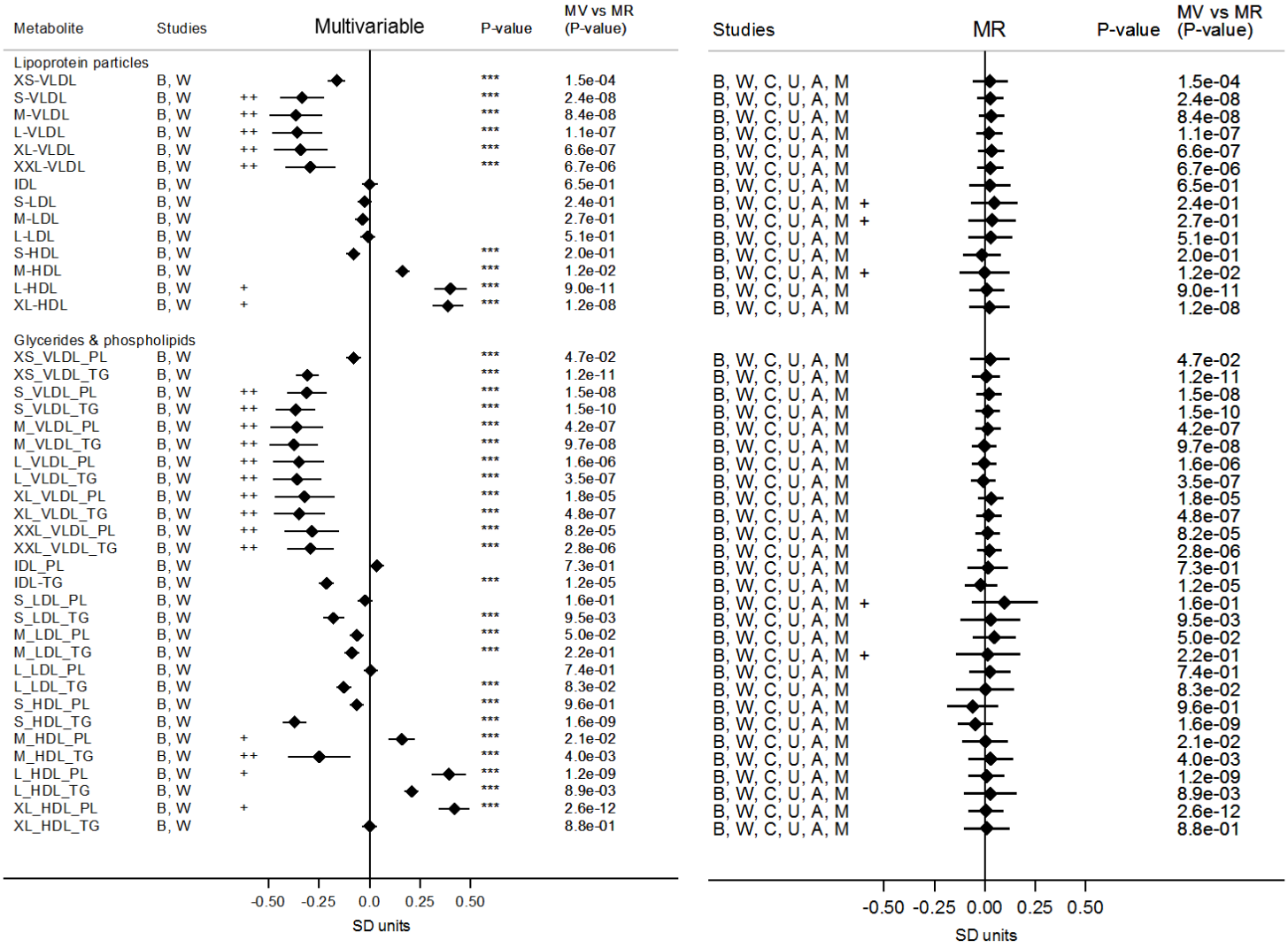
Supplementary figure 8. Association of multiple metabolic measures with blood adiponectin levels from observational and Mendelian randomization analysis among younger individuals (< 65 years old) free from cardiovascular disease.

Values are expressed as units of standardized log metabolite concentration (and 95% CI) per 1 unit increment of standardized log adiponectin levels. P-values for the association between adiponectin and metabolites are indicated by three asterisks ("***") if lower than Bonferroni-adjusted threshold (P-value < 0.0019). Heterogeneity was considered substantial if I^2 = 50-75% ("+") or very high if I^2 > 75% ("++"). P-values for the comparison between multivariable and Mendelian randomization estimates are displayed in the column "MR vs MV (P-value)". Metabolic measures were adjusted for age, sex, and, if applicable, place of recruitment (BWHHS and UKCTOCS) or principal components of genomic ancestry (PEL82 and some studies contributing to Metabolomics consortium) and the resulting residuals were transformed to normal distribution by inverse rank-based normal transformation. TotFA: total fatty acids, SFA: saturated fatty acid, MUFA: monounsaturated fatty acid, PUFA: polyunsaturated fatty acids, FAw6: omega-6 fatty acid, LA: linoleic acid, FAw3: omega-3 fatty acid, DHA: docosaexaenoic acid, CLA: conjugated linoleic acids, HbA1c: glycated haemoglobin, CRP: c-reactive protein, IL-6: interleukin-6, GlycA: glycoprotein acetyls, SBP: systolic blood pressure, DBP: diastolic blood pressure, P: 1982 Pelotas Birth Cohort, B: British Women Heart and Health Study, W: Whitehall II Study, U: UKCTOCS nested case-control study, A: The Avon Longitudinal Study of Children and Parents – mothers' cohort, M: Metabolomics consortium, SD units: standard deviation units, CI: confidence interval.



Supplementary figure 9. Association of metabolic measures not included in the main results with blood adiponectin levels from observational and Mendelian randomization analysis

Values are expressed as units of standardized log metabolite concentration (and 95% CI) per 1 unit increment of standardized log adiponectin levels. P-values for the association between adiponectin and metabolites are indicated by three asterisks ("***") if lower than Bonferroni-adjusted threshold (P-value < 0.0019). Heterogeneity was considered substantial if I^2 = 50-75% ("+") or very high if I^2 > 75% ("++"). P-values for the comparison between multivariable and Mendelian randomization estimates are displayed in the column "MR vs MV (P-value)". Metabolic measures were adjusted for age, sex, and, if applicable, place of recruitment (BWHHS and UKCTOCS) or principal components of genomic ancestry (PEL82 and some studies contributing to Metabolomics consortium) and the resulting residuals were transformed to normal distribution by inverse rank-based normal transformation. XXL: extremely large, XL: very large, L: large, M: medium, S: small, XS: very small, VLDL: very low-density lipoprotein, LDL: low-density lipoprotein, IDL: intermediate-density lipoprotein, HDL: high-density lipoprotein, c: cholesterol, DAG: diglycerides, TG: triglycerides, C: cholesterol, CE: cholesterol esters, FC: free cholesterol, P: 1982 Pelotas Birth Cohort, B: British Women Heart and Health Study, W: Whitehall II Study, U: UKCTOCS nested case-control study, A: The Avon Longitudinal Study of Children and Parents – mothers' cohort, SD units: standard deviation units, CI: confidence interval.



Supplementary figure 10. Association of metabolic measures not included in the main results with blood adiponectin levels from observational and Mendelian randomization analysis

Values are expressed as units of standardized log metabolite concentration (and 95% CI) per 1 unit increment of standardized log adiponectin levels. P-values for the association between adiponectin and metabolites are indicated by three asterisks ("***") if lower than Bonferroni-adjusted threshold (P-value < 0.0019). Heterogeneity was considered substantial if I^2 = 50-75% ("+") or very high if I^2 > 75% ("++"). P-values for the comparison between multivariable and Mendelian randomization estimates are displayed in the column "MR vs MV (P-value)". Metabolic measures were adjusted for age, sex, and, if applicable, place of recruitment (BWHHS and UKCTOCS) or principal components of genomic ancestry (PEL82 and some studies contributing to Metabolomics consortium) and the resulting residuals were transformed to normal distribution by inverse rank-based normal transformation. XXL: extremely large, XL: very large, L: large, M: medium, S: small, XS: very small, VLDL: very low-density lipoprotein, LDL: low-density lipoprotein, IDL: intermediate-density lipoprotein, HDL: high-density lipoprotein, c: cholesterol, DAG: diglycerides, TG: triglycerides, PL: phospholipids, P: 1982 Pelotas Birth Cohort, B: British Women Heart and Health Study, W: Whitehall II Study, U: UKCTOCS nested case-control study, A: The Avon Longitudinal Study of Children and Parents – mothers' cohort, SD units: standard deviation units, CI: confidence interval.

Supplementary table 1A – Estimated power in Multivariable regression analysis

Exposure	Outcome	Sample size*	Type-I error rate	Effect estimate†	Power
Adiponectin	Metabolic measure	3,006	0.05	0.20	100%
Adiponectin	Metabolic measure	3,006	0.05	0.10	100%
Adiponectin	Metabolic measure	3,006	0.05	0.05	78%

* Median sample size

† Considering the true underlying causal association is unknown, a range of values (in standard deviation units) was used.

Supplementary table 1B – Estimated power in Mendelian randomization analysis

Exposure	Outcome	Sample size*	Type-I error rate	Effect estimate†	Instrument strength (R^2) ‡	Power§
Adiponectin	Metabolic measure	23,884	0.05	0.20	0.04	88%
Adiponectin	Metabolic measure	23,884	0.05	0.10	0.04	87%
Adiponectin	Metabolic measure	23,884	0.05	0.05	0.04	34%

* Median sample size used for estimating SNP-outcome association

† Considering the true underlying causal association is unknown, a range of values (in standard deviation units) was used.

‡ Instrument strength relates to the proportion of variance in the exposure explained by the instrument (R^2). This was calculated by the sum of R^2 from each 4 SNPs in the instrument. The formula used to estimate R^2 for each SNP is detailed in Supplementary methods.

§ We have estimated power for our Mendelian randomization analyses using the online calculator tool (http://cnsgenomics.com/shiny/mRnd/) and assuming a range of effect sizes for the potential underlying causal association between exposure and outcome.

Supplementary table 2 – Total sample size per metabolite of multivariable and Mendelian randomization analysis

Metabolic measure	Group	N (multivariable analysis)	N (Mendelian randomization analysis)
Acetoacetate	Ketone bodies	3008	28225
Acetate	Ketone bodies	3008	34923
Alanine	Amino acids	3006	34969
Albumin	Fluid balance	3007	29139
ApoA-I	Apolipoproteins	3008	28326
ApoB	Apolipoproteins	3008	30868
3-OH-butyrate	Ketone bodies	3003	34295
Citrate	Glycolysis metabolites	3003	34937
CLA	Fatty acids	2498	5549
Creatinine	Fluid balance	2939	34756
CRP	Inflammation	5826	11039
DAG	Glycerides & phospholipids	2470	6521
DBP	Blood pressure	5909	11821
DHA	Fatty acids	2958	23497
Esterified cholesterol	Cholesterol	2960	23498
FAw3	Fatty acids	2959	22985
FAw6	Fatty acids	2958	23504
Fibrinogen	Inflammation	3029	5675
Free cholesterol	Cholesterol	2959	23497
Glucose	Glycemic traits	5720	37545
Glutamine	Amino acids	3006	34570
Glycerol	Glycolysis metabolites	2975	26391
Glycine	Amino acids	2954	24919
GlycA	Inflammation	3009	29446
HbA1c	Glycemic traits	3239	4647
HDL2-c	Cholesterol	3008	10183
HDL3-c	Cholesterol	3008	10183
HDL-c	Cholesterol	5762	30202
HDLd	Lipoprotein particle size	3008	29452
HDL-TG	Glycerides & phospholipids	3008	10183
Histidine	Amino acids	2976	29387
IDL	Lipoprotein lipid concentration	3008	29452
IL-6	Inflammation	3106	5585
Isoleucine	Amino acids	3008	34947
Insulin	Glycemic traits	3155	8148
LA	Fatty acids	2958	23524
Lactate	Glycolysis metabolites	3009	35047
LDL-c	Cholesterol	5762	34492
LDLd	Lipoprotein particle size	3008	29452
LDL-TG	Glycerides & phospholipids	3008	10183
Leucine	Amino acids	3009	34905
L-HDL	Lipoprotein lipid concentration	3009	29458
L-LDL	Lipoprotein lipid concentration	3009	29458
L-VLDL	Lipoprotein lipid concentration	3009	29146
M-HDL	Lipoprotein lipid concentration	3009	29458
M-LDL	Lipoprotein lipid concentration	3009	29458
MUFA	Fatty acids	2958	23522
M-VLDL	Lipoprotein lipid concentration	3009	29458
Phosphatidylcholines	Glycerides & phospholipids	2960	23502
Phenilalanine	Amino acids	3004	32833
PUFA	Fatty acids	2958	10003
Pyruvate	Glycolysis metabolites	3003	31327
Remnant-c	Cholesterol	3008	10183
SBP	Blood pressure	5909	11822
Total cholesterol	Cholesterol	5762	30763
Triglycerides	Glycerides & phospholipids	5762	34478
SFA	Fatty acids	2957	9988
S-HDL	Lipoprotein lipid concentration	3009	29458
S-LDL	Lipoprotein lipid concentration	3009	29458
Sphingomyelins	Glycerides & phospholipids	2959	20854
S-VLDL	Lipoprotein lipid concentration	3009	29458
Total cholines	Glycerides & phospholipids	2960	10007
TotFA	Fatty acids	2959	23503
Phosphoglycerides	Glycerides & phospholipids	2960	23521
Tyrosine	Amino acids	2994	35078
Valine	Amino acids	3009	35069
Viscosity	Inflammation	3094	4807
VLDL-c	Cholesterol	3008	10183
VLDLd	Lipoprotein particle size	3008	29452
VLDL-TG	Glycerides & phospholipids	3008	10183
XL-HDL	Lipoprotein lipid concentration	3009	29458
XL-VLDL	Lipoprotein lipid concentration	3009	29458
XS-VLDL	Lipoprotein lipid concentration	3009	29458
XXL-VLDL	Lipoprotein lipid concentration	3009	29146

Supplementary table 3 – Mean (and 95% confidence interval) of metabolic measures for each study that contributed with individual level data

		PEL82		BWHHS		WHII		CaPS		UKCTOCS		ALSPAC-M	
Metabolite	Units	N	Mean (95% CI)	N	Mean (95% CI)	N	Mean (95% CI)	N	Mean (95% CI)	N	Mean (95% CI)	N	Mean (95% CI)
Acetoacetate	mmol/L			3774	0.07 (0.07; 0.07)	4639	0.06 (0.06; 0.06)			4812	0.03 (0.03; 0.03)	4134	0.03 (0.03; 0.03)
Acetate	mmol/L			3774	0.04 (0.04; 0.04)	4638	0.07 (0.07; 0.07)	1223	0.09 (0.09; 0.09)	4811	0.05 (0.05; 0.05)	4135	0.06 (0.06; 0.07)
Alanine	mmol/L			3774	0.33 (0.33; 0.34)	4637	0.42 (0.42; 0.42)	1223	0.39 (0.38; 0.39)	4811	0.52 (0.52; 0.52)	4135	0.25 (0.25; 0.25)
Albumin	signal area			3779	0.1 (0.1; 0.1)	4638	0.1 (0.1; 0.1)	1223	0.08 (0.08; 0.09)	4811	0.09 (0.09; 0.09)	4138	0.09 (0.09; 0.09)
ApoA-I	g/L			3777	1.73 (1.72; 1.74)	4639	1.59 (1.59; 1.6)	1223	1.25 (1.24; 1.25)	4810	1.69 (1.68; 1.69)	4138	1.69 (1.68; 1.69)
ApoB	g/L			3777	1.15 (1.14; 1.16)	4639	0.98 (0.97; 0.98)	1223	0.94 (0.93; 0.96)	4810	0.95 (0.94; 0.96)	4138	0.86 (0.86; 0.87)
3-OH-butyrate	mmol/L			3773	0.19 (0.19; 0.2)	4631	0.15 (0.15; 0.16)	1205	0.12 (0.12; 0.13)	4797	0.18 (0.18; 0.18)	4129	0.11 (0.11; 0.12)
Citrate	mmol/L			3774	0.12 (0.12; 0.12)	4631	0.13 (0.13; 0.13)	1220	0.11 (0.11; 0.12)	4812	0.13 (0.13; 0.13)	4134	0.09 (0.09; 0.09)
CLA	mmol/L					4557	0.05 (0.05; 0.05)	104	0.03 (0.02; 0.03)			3950	0.02 (0.02; 0.02)
Creatinine	mmol/L			3469	0.06 (0.06; 0.06)	4592	0.08 (0.08; 0.08)	1222	0.07 (0.07; 0.07)	4803	0.06 (0.06; 0.06)	4134	0.06 (0.06; 0.06)
CRP	mg/dL	3524	3.93 (3.75; 4.11)	3709	3.49 (3.3; 3.68)	4712	2.07 (1.96; 2.18)	841	2.73 (2.48; 2.98)			4160	2.3 (2.13; 2.48)
DAG	mmol/L					4512	0.02 (0.02; 0.02)	1184	0.02 (0.02; 0.02)			3830	0.01 (0.01; 0.01)
DBP	mmHg	3580	75.45 (75.15; 75.76)	3964	79.42 (79.05; 79.79)	4874	77.45 (77.16; 77.74)	1206	84.78 (84.12; 85.43)			4570	72.72 (72.42; 73.02)
DHA	mmol/L			3769	0.3 (0.3; 0.3)	4558	0.19 (0.19; 0.2)	1219	0.12 (0.11; 0.12)	4797	0.19 (0.19; 0.19)	3954	0.15 (0.14; 0.15)
Esterified cholesterol	mmol/L			3769	4.22 (4.19; 4.25)	4561	3.66 (3.64; 3.68)	1220	2.72 (2.68; 2.76)	4797	3.56 (3.54; 3.58)	3953	3.27 (3.26; 3.29)
FAw3	mmol/L			3769	0.73 (0.72; 0.74)	4559	0.53 (0.53; 0.54)	1219	0.33 (0.33; 0.34)	4797	0.54 (0.53; 0.54)	3954	0.44 (0.43; 0.44)
FAw6	mmol/L			3769	4.63 (4.6; 4.66)	4558	4.14 (4.12; 4.16)	1219	3.03 (2.99; 3.07)	4797	3.97 (3.94; 3.99)	3953	3.71 (3.69; 3.73)
Fibrinogen	mmol/L			3817	3.45 (3.43; 3.47)	4620	3.02 (3; 3.04)	847	3.04 (2.99; 3.1)				
Free cholesterol	mmol/L			3769	1.77 (1.75; 1.78)	4560	1.42 (1.41; 1.43)	1220	1.2 (1.19; 1.22)	4797	1.39 (1.38; 1.4)	3953	1.36 (1.35; 1.37)
Glucose	mmol/L	3524	4.97 (4.92; 5.02)	3774	4.94 (4.89; 4.98)	4568	5.15 (5.12; 5.18)	1222	4.07 (4; 4.14)	4778	2.64 (2.58; 2.69)	4133	4.48 (4.45; 4.51)
Glutamine	mmol/L			3773	0.49 (0.49; 0.5)	4636	0.61 (0.61; 0.61)	1166	0.39 (0.39; 0.39)	4798	0.52 (0.52; 0.52)	4134	0.47 (0.47; 0.47)
Glycerol	mmol/L			3699	0.13 (0.13; 0.14)	4600	0.1 (0.1; 0.1)			4777	0.11 (0.11; 0.11)		
Glycine	mmol/L			3774	0.3 (0.3; 0.31)	4559	0.29 (0.29; 0.29)			4808	0.37 (0.37; 0.38)		
GlycA	mmol/L			3774	1.6 (1.59; 1.62)	4640	1.44 (1.43; 1.44)	1223	1.33 (1.32; 1.35)	4812	1.59 (1.58; 1.6)	4135	1.25 (1.24; 1.25)
HbA1c	%	3537	5.12 (5.1; 5.13)	3703	5.01 (4.98; 5.03)								
HDL2-c	mmol/L			3777	1.15 (1.13; 1.16)	4639	1.04 (1.03; 1.05)	1223	0.47 (0.45; 0.48)	4810	1.09 (1.08; 1.1)	4138	1.15 (1.14; 1.16)
HDL3-c	mmol/L			3777	0.52 (0.52; 0.52)	4639	0.48 (0.48; 0.48)	1223	0.42 (0.42; 0.43)	4810	0.55 (0.55; 0.55)	4138	0.55 (0.55; 0.55)
HDL-c	mmol/L	3524	1.52 (1.5; 1.53)	3777	1.67 (1.65; 1.68)	4639	1.52 (1.51; 1.53)	1223	0.89 (0.88; 0.9)	4810	1.64 (1.63; 1.66)	4138	1.7 (1.69; 1.71)
HDLd	nm			3777	9.98 (9.97; 9.99)	4639	10.03 (10.03; 10.04)	1223	9.57 (9.56; 9.58)	4810	10.01 (10; 10.02)	4138	10.09 (10.09; 10.1)
HDL-TG	mmol/L			3777	0.17 (0.17; 0.18)	4639	0.14 (0.14; 0.14)	1223	0.15 (0.14; 0.15)	4810	0.19 (0.19; 0.19)	4138	0.14 (0.14; 0.14)
Histidine	mmol/L			3774	0.06 (0.06; 0.06)	4585	0.08 (0.07; 0.08)	1223	0.06 (0.06; 0.06)	4807	0.08 (0.08; 0.08)	4134	0.06 (0.06; 0.06)
IDL	mmol/L			3777	1.53 (1.51; 1.54)	4639	1.33 (1.32; 1.34)	1223	1.03 (1.01; 1.04)	4810	1.17 (1.16; 1.18)	4138	1.12 (1.11; 1.13)
IL-6	pg/mL			3815	3.23 (3.1; 3.37)	4732	1.82 (1.77; 1.86)	701	3.38 (2.16; 4.61)				
Isoleucine	mmol/L			3774	0.06 (0.06; 0.06)	4639	0.06 (0.06; 0.06)	1222	0.06 (0.06; 0.07)	4811	0.07 (0.07; 0.07)	4133	0.03 (0.03; 0.03)
Insulin	mIU/L			3831	9.58 (8.78; 10.38)	4809	9.65 (9.29; 10)	608	5.85 (5.46; 6.23)			4092	5.24 (5.08; 5.4)
LA	mmol/L			3769	3.76 (3.74; 3.79)	4558	3.37 (3.36; 3.39)	1219	2.5 (2.46; 2.54)	4797	3.15 (3.13; 3.17)	3953	2.93 (2.91; 2.94)
Lactate	mmol/L			3774	1.64 (1.63; 1.66)	4640	1.91 (1.9; 1.93)	1223	1.74 (1.72; 1.76)	4812	5.58 (5.53; 5.63)	4135	0.8 (0.79; 0.81)
LDL-c	mmol/L	3524	2.83 (2.8; 2.85)	3777	2.42 (2.4; 2.44)	4639	1.88 (1.86; 1.89)	1223	1.6 (1.57; 1.63)	4810	1.8 (1.79; 1.82)	4138	1.56 (1.54; 1.57)
LDLd	mmol/L			3777	23.52 (23.52; 23.53)	4639	23.68 (23.68; 23.69)	1223	23.51 (23.5; 23.51)	4810	23.45 (23.45; 23.45)	4138	23.62 (23.62; 23.62)
LDL-TG	mmol/L			3777	0.28 (0.27; 0.28)	4639	0.19 (0.19; 0.19)	1223	0.17 (0.17; 0.17)	4810	0.26 (0.26; 0.26)	4138	0.17 (0.17; 0.17)
Leucine	mmol/L			3774	0.07 (0.07; 0.07)	4639	0.09 (0.09; 0.09)	1223	0.08 (0.08; 0.08)	4812	0.1 (0.1; 0.1)	4134	0.05 (0.05; 0.05)
L-HDL	mmol/L			3780	0.82 (0.81; 0.84)	4641	0.81 (0.8; 0.82)	1225	0.26 (0.25; 0.27)	4813	0.94 (0.93; 0.95)	4138	1 (0.99; 1.01)
L-LDL	mmol/L			3780	1.83 (1.82; 1.85)	4641	1.47 (1.46; 1.48)	1225	1.22 (1.2; 1.24)	4813	1.39 (1.38; 1.4)	4138	1.24 (1.22; 1.25)
L-VLDL	mmol/L			3780	0.33 (0.32; 0.34)	4641	0.19 (0.19; 0.2)	1225	0.44 (0.42; 0.46)	4813	0.33 (0.32; 0.34)	4138	0.17 (0.16; 0.17)
M-HDL	mmol/L			3780	1.04 (1.03; 1.05)	4641	0.99 (0.98; 0.99)	1225	0.62 (0.61; 0.63)	4813	0.95 (0.94; 0.96)	4138	1.03 (1.02; 1.03)
M-LDL	mmol/L			3780	1.08 (1.07; 1.09)	4641	0.82 (0.81; 0.82)	1225	0.73 (0.72; 0.74)	4813	0.84 (0.83; 0.84)	4138	0.69 (0.68; 0.69)
MUFA	mmol/L			3769	3.13 (3.1; 3.17)	4558	3 (2.98; 3.02)	1219	2.72 (2.66; 2.77)	4761	3.6 (3.57; 3.63)	3951	2.81 (2.79; 2.84)
M-VLDL	mmol/L			3780	0.71 (0.69; 0.72)	4641	0.53 (0.52; 0.54)	1225	0.83 (0.81; 0.86)	4813	0.68 (0.67; 0.69)	4138	0.41 (0.4; 0.42)
Phosphatidylcholines	mmol/L			3769	2.49 (2.47; 2.5)	4561	2.01 (2; 2.02)	1219	1.56 (1.55; 1.58)	4713	2.1 (2.09; 2.11)	3930	2.03 (2.02; 2.04)
Phenilalanine	mmol/L			3774	0.08 (0.08; 0.08)	4633	0.08 (0.08; 0.08)	1223	0.07 (0.07; 0.08)	4812	0.1 (0.1; 0.1)	4132	0.04 (0.04; 0.04)
PUFA	mmol/L			3769	5.36 (5.32; 5.4)	4558	4.67 (4.64; 4.69)	1219	3.36 (3.32; 3.41)	4797	4.5 (4.48; 4.53)	3953	4.15 (4.13; 4.17)
Pyruvate	mmol/L			3772	0.1 (0.1; 0.1)	4633	0.09 (0.09; 0.09)			4808	0.23 (0.22; 0.24)	4135	0.09 (0.09; 0.09)
Remnant-c	mmol/L			3777	1.9 (1.88; 1.91)	4639	1.69 (1.68; 1.7)	1223	1.44 (1.41; 1.46)	4810	1.5 (1.48; 1.51)	4138	1.38 (1.37; 1.39)
SBP	mmHg	3580	121.29 (120.84; 121.74)	3964	147.11 (146.33; 147.9)	4874	122.85 (122.4; 123.31)	1207	146.19 (144.91; 147.47)			4570	118.46 (118.09; 118.82)
Total cholesterol	mmol/L	3524	4.94 (4.91; 4.98)	3777	5.98 (5.94; 6.03)	4639	5.08 (5.06; 5.11)	1223	3.93 (3.88; 3.98)	4810	4.94 (4.91; 4.97)	4138	4.63 (4.61; 4.66)
Triglycerides	mmol/L	3524	1.37 (1.33; 1.41)	3777	1.68 (1.65; 1.71)	4639	1.22 (1.21; 1.23)	1223	1.68 (1.64; 1.73)	4810	1.68 (1.66; 1.71)	4138	1.06 (1.04; 1.07)
SFA	mmol/L			3769	4.91 (4.88; 4.95)	4557	4.56 (4.54; 4.59)	1219	4.05 (3.99; 4.11)	4761	4.82 (4.79; 4.85)	3949	4.15 (4.13; 4.18)
S-HDL	mmol/L			3780	1.24 (1.23; 1.24)	4641	1.09 (1.08; 1.09)	1225	0.98 (0.97; 0.99)	4813	1.21 (1.2; 1.21)	4138	1.12 (1.12; 1.13)
S-LDL	mmol/L			3780	0.68 (0.68; 0.69)	4641	0.52 (0.51; 0.52)	1225	0.46 (0.45; 0.47)	4813	0.55 (0.54; 0.55)	4138	0.45 (0.44; 0.45)
Sphingomyelins	mmol/L			3769	0.61 (0.6; 0.61)	4560	0.5 (0.5; 0.5)	1220	0.45 (0.44; 0.45)	4786	0.5 (0.5; 0.5)		
S-VLDL	mmol/L			3780	0.79 (0.77; 0.8)	4641	0.66 (0.66; 0.67)	1225	0.71 (0.7; 0.72)	4813	0.74 (0.73; 0.75)	4138	0.55 (0.54; 0.55)
Total cholines	mmol/L			3769	2.95 (2.93; 2.97)	4561	2.41 (2.4; 2.42)	1220	1.84 (1.82; 1.87)	4797	2.46 (2.45; 2.47)	3953	2.35 (2.34; 2.36)
TotFA	mmol/L			3769	13.41 (13.32; 13.51)	4559	12.23 (12.17; 12.29)	1219	10.13 (9.98; 10.28)	4797	12.94 (12.86; 13.02)	3952	11.12 (11.05; 11.18)
Phosphoglycerides	mmol/L			3769	2.44 (2.42; 2.46)	4561	2.04 (2.03; 2.05)	1220	1.52 (1.5; 1.54)	4797	2 (1.99; 2.01)	3951	1.94 (1.92; 1.95)
Tyrosine	mmol/L			3774	0.05 (0.05; 0.05)	4615	0.06 (0.06; 0.06)	1222	0.05 (0.05; 0.05)	4805	0.07 (0.07; 0.07)	4132	0.05 (0.05; 0.05)
Valine	mmol/L			3774	0.17 (0.16; 0.17)	4640	0.2 (0.2; 0.2)	1221	0.16 (0.16; 0.17)	4810	0.2 (0.2; 0.2)	4133	0.14 (0.14; 0.15)
Viscosity	mPa.s.			3636	1.3 (1.3; 1.3)	4741	1.26 (1.25; 1.26)						
VLDL-c	mmol/L			3777	0.94 (0.93; 0.95)	4639	0.84 (0.83; 0.84)	1223	0.8 (0.79; 0.82)	4810	0.8 (0.79; 0.81)	4138	0.67 (0.66; 0.68)
VLDLd	mmol/L			3777	36.31 (36.27; 36.36)	4639	35.82 (35.79; 35.84)	1223	37.77 (37.7; 37.83)	4810	36.51 (36.47; 36.55)	4138	35.78 (35.74; 35.82)
VLDL-TG	mmol/L			3777	1.07 (1.04; 1.09)	4639	0.77 (0.75; 0.78)	1223	1.25 (1.21; 1.29)	4810	1.07 (1.05; 1.09)	4138	0.64 (0.63; 0.65)
XL-HDL	mmol/L			3780	0.52 (0.51; 0.53)	4641	0.47 (0.47; 0.48)	1225	0.16 (0.15; 0.17)	4813	0.51 (0.5; 0.52)	4138	0.55 (0.54; 0.56)
XL-VLDL	mmol/L			3780	0.08 (0.08; 0.08)	4641	0.04 (0.04; 0.04)	1225	0.11 (0.1; 0.11)	4813	0.08 (0.07; 0.08)	4138	0.04 (0.04; 0.04)
XS-VLDL	mmol/L			3780	0.69 (0.68; 0.69)	4641	0.64 (0.64; 0.65)	1225	0.49 (0.49; 0.5)	4813	0.59 (0.58; 0.59)	4138	0.54 (0.53; 0.54)
XXL-VLDL	mmol/L			3780	0.03 (0.03; 0.03)	4641	0.02 (0.02; 0.02)	1225	0.04 (0.04; 0.04)	4813	0.03 (0.03; 0.03)	4138	0.02 (0.02; 0.02)

Supplementary table 4A – Multivariable regression estimates for each contributing study

	PEL82	BWHHS	WHII
Metabolite	Mean SD units (95% CI)	Mean SD units (95% CI)	Mean SD units (95% CI)
3-OH-butyrate		0.12 (0.03; 0.2)	0.04 (0.01; 0.08)
Acetate		0.05 (-0.04; 0.14)	0.02 (-0.02; 0.05)
Acetoacetate		0.11 (0.02; 0.2)	0.09 (0.05; 0.13)
Alanine		-0.13 (-0.22; -0.04)	-0.21 (-0.25; -0.17)
Albumin		0.04 (-0.05; 0.12)	-0.01 (-0.05; 0.02)
ApoA-I		0.31 (0.22; 0.39)	0.27 (0.24; 0.31)
ApoB		-0.25 (-0.34; -0.16)	-0.11 (-0.15; -0.07)
CLA			-0.05 (-0.09; -0.01)
CRP	-0.17 (-0.2; -0.13)	-0.17 (-0.26; -0.08)	-0.19 (-0.22; -0.15)
Citrate		0.1 (0.01; 0.19)	0.01 (-0.03; 0.05)
Creatinine		-0.05 (-0.15; 0.05)	-0.1 (-0.13; -0.06)
DAG			-0.25 (-0.29; -0.21)
DBP	-0.1 (-0.14; -0.07)	0.01 (-0.08; 0.1)	-0.11 (-0.15; -0.07)
DHA		-0.01 (-0.1; 0.08)	-0.06 (-0.1; -0.02)
Esterified cholesterol		0.03 (-0.06; 0.13)	0.07 (0.03; 0.11)
FAw3		0.02 (-0.07; 0.11)	-0.05 (-0.09; -0.01)
FAw6		0.03 (-0.06; 0.13)	-0.02 (-0.06; 0.02)
Fibrinogen		-0.05 (-0.13; 0.04)	-0.1 (-0.14; -0.06)
Free cholesterol		0.03 (-0.06; 0.13)	0.1 (0.06; 0.14)
Glucose	-0.13 (-0.17; -0.09)	-0.06 (-0.15; 0.02)	-0.12 (-0.16; -0.08)
Glutamine		0.08 (-0.01; 0.17)	0.08 (0.04; 0.12)
GlycA		-0.3 (-0.39; -0.22)	-0.27 (-0.31; -0.24)
Glycerol		0.01 (-0.09; 0.1)	-0.1 (-0.13; -0.06)
Glycine		0.22 (0.13; 0.32)	0.08 (0.04; 0.12)
HDL-TG		-0.26 (-0.35; -0.17)	-0.14 (-0.17; -0.1)
HDL-c	0.31 (0.28; 0.35)	0.44 (0.35; 0.52)	0.34 (0.31; 0.38)
HDL2-c		0.44 (0.36; 0.53)	0.36 (0.32; 0.39)
HDL3-c		0.19 (0.1; 0.28)	0.19 (0.16; 0.23)
HDLd		0.48 (0.4; 0.56)	0.39 (0.35; 0.42)
HbA1c	-0.07 (-0.11; -0.04)	-0.16 (-0.25; -0.06)	
Histidine		-0.03 (-0.12; 0.06)	-0.04 (-0.08; 0)
IDL		-0.03 (-0.12; 0.07)	0.02 (-0.02; 0.06)
IL-6		-0.15 (-0.24; -0.06)	-0.17 (-0.21; -0.14)
Insulin		-0.38 (-0.46; -0.3)	-0.34 (-0.37; -0.3)
Isoleucine		-0.38 (-0.46; -0.29)	-0.36 (-0.4; -0.33)
L-HDL		0.45 (0.37; 0.53)	0.37 (0.33; 0.4)
L-LDL		-0.04 (-0.13; 0.06)	0.01 (-0.03; 0.04)
L-VLDL		-0.43 (-0.51; -0.34)	-0.3 (-0.33; -0.26)
LA		0.04 (-0.05; 0.14)	0 (-0.04; 0.04)
LDL-TG		-0.15 (-0.24; -0.05)	-0.13 (-0.16; -0.09)
LDL-c	-0.12 (-0.16; -0.09)	-0.03 (-0.12; 0.06)	0.01 (-0.03; 0.05)
LDLd		0.05 (-0.05; 0.14)	0.08 (0.04; 0.12)
Lactate		-0.16 (-0.25; -0.08)	-0.13 (-0.17; -0.09)
Leucine		-0.34 (-0.42; -0.26)	-0.34 (-0.38; -0.31)
M-HDL		0.21 (0.12; 0.29)	0.16 (0.13; 0.2)
M-LDL		-0.06 (-0.15; 0.03)	-0.02 (-0.06; 0.02)
M-VLDL		-0.44 (-0.52; -0.35)	-0.3 (-0.34; -0.26)
MUFA		-0.31 (-0.39; -0.22)	-0.14 (-0.18; -0.1)
PUFA		0.03 (-0.06; 0.12)	-0.03 (-0.07; 0.01)
Phenilalanine		-0.13 (-0.22; -0.05)	-0.19 (-0.23; -0.16)
Phosphatidylcholines		0.11 (0.03; 0.2)	0.11 (0.07; 0.15)
Phosphoglycerides		0.08 (-0.01; 0.17)	0.09 (0.05; 0.13)
Pyruvate		-0.17 (-0.26; -0.09)	-0.17 (-0.21; -0.13)
Remnant-c		-0.23 (-0.32; -0.14)	-0.09 (-0.13; -0.05)
S-HDL		-0.08 (-0.17; 0.01)	-0.06 (-0.1; -0.03)
S-LDL		-0.05 (-0.14; 0.04)	-0.01 (-0.05; 0.03)
S-VLDL		-0.39 (-0.48; -0.3)	-0.28 (-0.31; -0.24)
SBP	-0.09 (-0.13; -0.05)	-0.08 (-0.17; 0.01)	-0.08 (-0.11; -0.04)
SFA		-0.15 (-0.24; -0.06)	-0.15 (-0.19; -0.11)
Sphingomyelins		0.19 (0.1; 0.28)	0.13 (0.09; 0.17)
TotFA		-0.17 (-0.27; -0.08)	-0.12 (-0.16; -0.09)
Total cholesterol	-0.07 (-0.11; -0.03)	0.04 (-0.06; 0.13)	0.08 (0.04; 0.12)
Total cholines		0.14 (0.05; 0.23)	0.13 (0.09; 0.17)
Triglycerides	-0.27 (-0.31; -0.24)	-0.41 (-0.49; -0.32)	-0.3 (-0.34; -0.26)
Tyrosine		-0.16 (-0.25; -0.07)	-0.2 (-0.24; -0.17)
VLDL-TG		-0.43 (-0.52; -0.35)	-0.32 (-0.36; -0.28)
VLDL-c		-0.35 (-0.44; -0.26)	-0.2 (-0.24; -0.17)
VLDLd		-0.44 (-0.52; -0.35)	-0.32 (-0.36; -0.28)
Valine		-0.28 (-0.36; -0.19)	-0.34 (-0.37; -0.3)
Viscosity		-0.15 (-0.24; -0.05)	-0.13 (-0.17; -0.09)
XL-HDL		0.44 (0.35; 0.52)	0.36 (0.32; 0.39)
XL-VLDL		-0.41 (-0.5; -0.33)	-0.28 (-0.31; -0.24)
XS-VLDL		-0.18 (-0.28; -0.09)	-0.13 (-0.17; -0.09)
XXL-VLDL		-0.36 (-0.45; -0.27)	-0.24 (-0.27; -0.2)

Supplementary table 4B – Mendelian randomization estimates for each contributing study

	PEL82	BWHHS	WHII	CaPS	UKCTOCS	ALSPAC-M	Metabolomics consortium
Metabolite	Mean SD units (95% CI)	Mean SD units (95% CI)	Mean SD units (95% CI)	Mean SD units (95% CI)	Mean SD units (95% CI)	Mean SD units (95% CI)	Mean SD units (95% CI)
3-OH-butyrate		0.07 (-0.19; 0.33)	-0.02 (-0.22; 0.18)	0.13 (-0.18; 0.44)	-0.01 (-0.29; 0.27)	-0.04 (-0.22; 0.15)	0.02 (-0.05; 0.1)
Acetate		0.24 (-0.01; 0.5)	0.12 (-0.08; 0.32)	-0.14 (-0.45; 0.17)	0.29 (0.01; 0.56)	0.01 (-0.17; 0.2)	0.03 (-0.04; 0.1)
Acetoacetate		0.11 (-0.15; 0.37)	-0.13 (-0.33; 0.07)		-0.22 (-0.51; 0.07)	0 (-0.18; 0.19)	-0.02 (-0.1; 0.06)
Alanine		-0.03 (-0.29; 0.23)	0.06 (-0.14; 0.26)	0.08 (-0.24; 0.39)	-0.04 (-0.33; 0.25)	0.07 (-0.11; 0.26)	0.02 (-0.06; 0.09)
Albumin		-0.02 (-0.27; 0.24)	-0.02 (-0.22; 0.18)	-0.2 (-0.51; 0.11)	0.23 (-0.06; 0.52)	0.12 (-0.06; 0.3)	0 (-0.09; 0.08)
ApoA-I		0.27 (0.01; 0.53)	0.17 (-0.03; 0.37)	-0.31 (-0.62; 0)	0.16 (-0.13; 0.45)	0.06 (-0.12; 0.24)	0 (-0.09; 0.08)
ApoB		0.02 (-0.24; 0.28)	0.15 (-0.05; 0.35)	0.08 (-0.23; 0.4)	0.29 (-0.01; 0.59)	-0.07 (-0.26; 0.11)	-0.01 (-0.09; 0.07)
CLA			0.34 (0.14; 0.54)	1.22 (0.19; 2.25)		-0.27 (-0.46; -0.08)	
CRP	0.03 (-0.16; 0.21)	0.26 (-0.01; 0.53)	-0.12 (-0.32; 0.07)	0.08 (-0.3; 0.46)		-0.04 (-0.23; 0.14)	
Citrate		-0.1 (-0.37; 0.17)	-0.07 (-0.27; 0.14)	-0.25 (-0.56; 0.06)	-0.19 (-0.48; 0.1)	0.02 (-0.17; 0.21)	-0.05 (-0.12; 0.03)
Creatinine		-0.25 (-0.54; 0.04)	0.21 (0.01; 0.42)	-0.3 (-0.61; 0.01)	0.17 (-0.14; 0.47)	-0.11 (-0.29; 0.08)	-0.03 (-0.1; 0.05)
DAG			0.16 (-0.04; 0.37)	-0.28 (-0.6; 0.04)		-0.12 (-0.32; 0.07)	
DBP	0.06 (-0.12; 0.24)	-0.18 (-0.43; 0.08)	0.02 (-0.18; 0.22)	0.12 (-0.19; 0.44)		0 (-0.18; 0.18)	
DHA		0.33 (0.07; 0.59)	0.32 (0.12; 0.52)	-0.19 (-0.5; 0.13)	0.37 (0.09; 0.65)	-0.04 (-0.23; 0.15)	-0.01 (-0.11; 0.09)
Esterified cholesterol		0.16 (-0.1; 0.42)	0.16 (-0.05; 0.36)	-0.06 (-0.38; 0.25)	0.44 (0.14; 0.74)	-0.11 (-0.3; 0.07)	0.04 (-0.05; 0.14)
FAw3		0.36 (0.1; 0.62)	0.26 (0.06; 0.46)	-0.14 (-0.45; 0.18)	0.47 (0.18; 0.75)	-0.14 (-0.32; 0.05)	0.01 (-0.09; 0.11)
FAw6		0.19 (-0.07; 0.46)	0.17 (-0.03; 0.37)	-0.13 (-0.45; 0.18)	0.36 (0.06; 0.65)	-0.04 (-0.23; 0.15)	0.04 (-0.06; 0.14)
Fibrinogen		-0.14 (-0.4; 0.12)	-0.05 (-0.25; 0.15)	-0.3 (-0.67; 0.08)			
Free cholesterol		0.13 (-0.14; 0.39)	0.15 (-0.06; 0.35)	-0.13 (-0.44; 0.18)	0.29 (-0.01; 0.59)	-0.15 (-0.34; 0.04)	0.01 (-0.09; 0.11)
Glucose	0.15 (-0.04; 0.33)	0.04 (-0.22; 0.3)	0.03 (-0.16; 0.22)	-0.21 (-0.52; 0.1)	-0.09 (-0.41; 0.23)	0.23 (0.05; 0.41)	-0.06 (-0.13; 0.01)
Glutamine		0.05 (-0.21; 0.31)	-0.28 (-0.48; -0.08)	0.11 (-0.21; 0.43)	-0.01 (-0.3; 0.29)	0.07 (-0.12; 0.25)	0.03 (-0.05; 0.1)
GlycA		0 (-0.26; 0.26)	0.18 (-0.02; 0.38)	0.04 (-0.28; 0.35)	0.22 (-0.06; 0.5)	0.05 (-0.13; 0.23)	-0.07 (-0.15; 0.01)
Glycerol		-0.07 (-0.34; 0.19)	-0.01 (-0.21; 0.2)		-0.02 (-0.32; 0.28)		0 (-0.08; 0.08)
Glycine		-0.17 (-0.43; 0.08)	-0.11 (-0.31; 0.1)		-0.13 (-0.42; 0.16)		-0.03 (-0.11; 0.06)
HDL-TG		-0.2 (-0.46; 0.06)	0.2 (0; 0.4)	-0.02 (-0.33; 0.29)	0.14 (-0.15; 0.44)	-0.09 (-0.28; 0.1)	
HDL-c	0 (-0.18; 0.19)	0.23 (-0.03; 0.49)	0.1 (-0.1; 0.31)	-0.35 (-0.66; -0.04)	0.03 (-0.26; 0.32)	0.05 (-0.13; 0.23)	0.07 (-0.01; 0.15)
HDL2-c		0.26 (0; 0.52)	0.1 (-0.1; 0.31)	-0.35 (-0.67; -0.04)	0 (-0.29; 0.29)	0.06 (-0.12; 0.25)	
HDL3-c		-0.01 (-0.28; 0.25)	0.06 (-0.14; 0.26)	-0.21 (-0.52; 0.11)	0.31 (0.02; 0.6)	-0.08 (-0.27; 0.1)	
HDLd		0.22 (-0.05; 0.48)	0.1 (-0.1; 0.31)	-0.2 (-0.51; 0.11)	-0.06 (-0.34; 0.22)	0.06 (-0.13; 0.24)	-0.03 (-0.11; 0.05)
HbA1c	-0.1 (-0.29; 0.08)	-0.22 (-0.49; 0.04)					
Histidine		0.19 (-0.06; 0.45)	-0.04 (-0.24; 0.17)	0.33 (0.02; 0.64)	0.12 (-0.16; 0.4)	0.06 (-0.13; 0.25)	0.03 (-0.06; 0.11)
IDL		0.05 (-0.21; 0.31)	0.1 (-0.1; 0.3)	0.05 (-0.26; 0.36)	0.35 (0.04; 0.65)	-0.11 (-0.3; 0.07)	-0.02 (-0.1; 0.06)
IL-6		-0.18 (-0.44; 0.09)	-0.06 (-0.26; 0.14)	-0.38 (-0.8; 0.03)			
Insulin		-0.21 (-0.47; 0.05)	-0.01 (-0.2; 0.18)	0.34 (-0.1; 0.78)		-0.08 (-0.27; 0.11)	
Isoleucine		-0.03 (-0.29; 0.23)	0.14 (-0.05; 0.34)	0.11 (-0.2; 0.43)	-0.07 (-0.36; 0.22)	0.04 (-0.15; 0.22)	0.01 (-0.07; 0.08)
L-HDL		0.17 (-0.09; 0.43)	0.07 (-0.13; 0.28)	-0.31 (-0.62; 0)	-0.01 (-0.29; 0.27)	0.05 (-0.13; 0.24)	-0.01 (-0.09; 0.07)
L-LDL		0.02 (-0.24; 0.29)	0.1 (-0.1; 0.31)	-0.03 (-0.34; 0.29)	0.38 (0.08; 0.68)	-0.12 (-0.31; 0.06)	-0.01 (-0.09; 0.07)
L-VLDL		-0.02 (-0.28; 0.24)	0.12 (-0.08; 0.32)	0.03 (-0.29; 0.34)	0.07 (-0.22; 0.35)	0.03 (-0.16; 0.21)	-0.04 (-0.12; 0.04)
LA		0.14 (-0.12; 0.41)	0.15 (-0.05; 0.35)	-0.1 (-0.42; 0.21)	0.26 (-0.04; 0.56)	-0.01 (-0.2; 0.18)	0.04 (-0.06; 0.14)
LDL-TG		-0.06 (-0.33; 0.21)	0.15 (-0.05; 0.35)	-0.06 (-0.38; 0.25)	0.29 (-0.01; 0.59)	-0.12 (-0.31; 0.06)	
LDL-c	-0.1 (-0.29; 0.08)	0.07 (-0.2; 0.33)	0.09 (-0.11; 0.29)	0 (-0.32; 0.31)	0.41 (0.1; 0.71)	-0.12 (-0.31; 0.06)	0 (-0.08; 0.08)
LDLd		-0.19 (-0.45; 0.07)	-0.06 (-0.26; 0.15)	0.27 (-0.04; 0.59)	-0.22 (-0.51; 0.07)	-0.08 (-0.26; 0.1)	-0.04 (-0.13; 0.04)
Lactate		-0.03 (-0.29; 0.23)	0.02 (-0.19; 0.22)	0.14 (-0.17; 0.45)	-0.02 (-0.31; 0.27)	-0.07 (-0.26; 0.11)	0.01 (-0.07; 0.08)
Leucine		-0.05 (-0.31; 0.21)	0.21 (0.01; 0.41)	0.28 (-0.03; 0.59)	-0.1 (-0.39; 0.18)	-0.01 (-0.19; 0.18)	0 (-0.07; 0.07)
M-HDL		0.19 (-0.07; 0.44)	0.09 (-0.11; 0.29)	-0.46 (-0.77; -0.15)	-0.08 (-0.38; 0.23)	0.03 (-0.16; 0.21)	0.04 (-0.04; 0.12)
M-LDL		0.02 (-0.24; 0.29)	0.1 (-0.1; 0.3)	-0.05 (-0.36; 0.27)	0.43 (0.12; 0.73)	-0.12 (-0.3; 0.07)	0 (-0.08; 0.08)
M-VLDL		-0.07 (-0.33; 0.19)	0.16 (-0.05; 0.36)	0.02 (-0.29; 0.33)	0.13 (-0.17; 0.42)	0.04 (-0.15; 0.22)	-0.03 (-0.12; 0.05)
MUFA		-0.11 (-0.37; 0.15)	0.2 (0; 0.41)	-0.04 (-0.35; 0.27)	0.28 (-0.01; 0.58)	-0.1 (-0.29; 0.09)	0.06 (-0.04; 0.16)
PUFA		0.24 (-0.02; 0.51)	0.22 (0.02; 0.42)	-0.15 (-0.46; 0.16)	0.39 (0.09; 0.69)	-0.05 (-0.24; 0.13)	
Phenilalanine		0.08 (-0.19; 0.34)	0.07 (-0.13; 0.27)	0.7 (0.39; 1.01)	0 (-0.28; 0.28)	-0.03 (-0.22; 0.16)	0.03 (-0.05; 0.1)
Phosphatidylcholines		0.2 (-0.06; 0.47)	0.2 (0; 0.41)	-0.29 (-0.61; 0.02)	0.3 (0; 0.6)	-0.06 (-0.25; 0.13)	0.08 (-0.02; 0.18)
Phosphoglycerides		0.15 (-0.11; 0.42)	0.18 (-0.03; 0.38)	-0.31 (-0.62; 0)	0.19 (-0.11; 0.48)	-0.06 (-0.25; 0.14)	0.1 (0; 0.2)
Pyruvate		-0.11 (-0.37; 0.16)	0.09 (-0.11; 0.29)		0.1 (-0.2; 0.41)	-0.07 (-0.25; 0.11)	-0.02 (-0.1; 0.06)
Remnant-c		0.02 (-0.24; 0.28)	0.15 (-0.05; 0.35)	0.14 (-0.17; 0.46)	0.28 (-0.03; 0.58)	-0.08 (-0.26; 0.11)	
S-HDL		-0.01 (-0.27; 0.25)	0.02 (-0.18; 0.22)	-0.41 (-0.72; -0.1)	0.1 (-0.2; 0.4)	-0.04 (-0.23; 0.14)	0.03 (-0.05; 0.11)
S-LDL		0.06 (-0.21; 0.32)	0.12 (-0.08; 0.32)	-0.07 (-0.38; 0.24)	0.43 (0.13; 0.73)	-0.11 (-0.29; 0.08)	-0.01 (-0.09; 0.07)
S-VLDL		-0.11 (-0.37; 0.15)	0.18 (-0.03; 0.38)	0.04 (-0.27; 0.35)	0.2 (-0.1; 0.49)	0.01 (-0.17; 0.2)	0.01 (-0.07; 0.09)
SBP	0.09 (-0.09; 0.28)	0.06 (-0.2; 0.32)	0 (-0.2; 0.19)	-0.22 (-0.53; 0.1)		0.03 (-0.15; 0.21)	
SFA		0.1 (-0.16; 0.37)	0.19 (-0.01; 0.39)	-0.04 (-0.35; 0.27)	0.29 (-0.01; 0.59)	-0.11 (-0.3; 0.08)	
Sphingomyelins		0.22 (-0.04; 0.49)	0.09 (-0.12; 0.29)	0.15 (-0.16; 0.46)	0.32 (0.02; 0.62)		-0.02 (-0.11; 0.08)
TotFA		0.07 (-0.19; 0.33)	0.22 (0.02; 0.43)	-0.09 (-0.4; 0.22)	0.34 (0.04; 0.64)	-0.11 (-0.3; 0.08)	0.06 (-0.04; 0.16)
Total cholesterol	-0.04 (-0.23; 0.14)	0.16 (-0.1; 0.42)	0.16 (-0.04; 0.36)	-0.03 (-0.34; 0.29)	0.4 (0.1; 0.7)	-0.1 (-0.28; 0.09)	0.03 (-0.05; 0.12)
Total cholines		0.22 (-0.04; 0.48)	0.16 (-0.05; 0.36)	-0.27 (-0.59; 0.04)	0.34 (0.05; 0.63)	-0.08 (-0.27; 0.11)	
Triglycerides	0.04 (-0.14; 0.23)	-0.07 (-0.33; 0.19)	0.15 (-0.05; 0.36)	0.01 (-0.3; 0.32)	0.15 (-0.14; 0.44)	-0.01 (-0.19; 0.17)	-0.01 (-0.09; 0.07)
Tyrosine		-0.2 (-0.47; 0.07)	0.06 (-0.14; 0.26)	0.38 (0.07; 0.69)	-0.12 (-0.41; 0.17)	-0.02 (-0.21; 0.17)	0.07 (-0.01; 0.14)
VLDL-TG		-0.04 (-0.3; 0.22)	0.14 (-0.07; 0.34)	0.03 (-0.28; 0.34)	0.1 (-0.18; 0.39)	0.04 (-0.14; 0.22)	
VLDL-c		-0.03 (-0.29; 0.23)	0.19 (-0.02; 0.39)	0.18 (-0.14; 0.49)	0.21 (-0.09; 0.5)	-0.03 (-0.22; 0.15)	
VLDLd		-0.08 (-0.33; 0.18)	0.04 (-0.16; 0.24)	-0.02 (-0.34; 0.29)	-0.04 (-0.32; 0.24)	0.09 (-0.1; 0.27)	-0.01 (-0.09; 0.07)
Valine		-0.15 (-0.41; 0.11)	0.11 (-0.08; 0.31)	0.14 (-0.18; 0.45)	-0.16 (-0.45; 0.14)	0.03 (-0.15; 0.22)	-0.02 (-0.09; 0.06)
Viscosity		-0.23 (-0.5; 0.05)	0.03 (-0.16; 0.23)				
XL-HDL		0.19 (-0.08; 0.45)	0.17 (-0.03; 0.37)	-0.17 (-0.48; 0.14)	0.04 (-0.25; 0.33)	0.06 (-0.12; 0.24)	-0.03 (-0.12; 0.05)
XL-VLDL		-0.05 (-0.31; 0.22)	0.12 (-0.08; 0.32)	0.1 (-0.22; 0.41)	0.01 (-0.27; 0.28)	0.03 (-0.15; 0.21)	0.01 (-0.07; 0.09)
XS-VLDL		-0.03 (-0.29; 0.23)	0.13 (-0.07; 0.33)	0.08 (-0.23; 0.39)	0.31 (0.01; 0.62)	-0.07 (-0.25; 0.11)	-0.01 (-0.09; 0.07)
XXL-VLDL		-0.07 (-0.33; 0.2)	0.14 (-0.06; 0.34)	0.13 (-0.18; 0.44)	-0.07 (-0.35; 0.22)	0 (-0.18; 0.19)	0.01 (-0.07; 0.09)

Supplementary table 5 – Heterogeneity estimates (I^2) for meta-analysis of study-specific multivariable (MV) and Mendelian randomization (MR) estimates

Metabolite	Overall		Females		Males		European studies only		Low risk individuals only	
	MV	MR	MV	MR	MV	MR	MV	MR	MV	MR
XXL-VLDL	85	0	82	7	NA	0	85	0	78	34
XL-VLDL	88	0	91	0	NA	0	88	0	79	0
L-VLDL	86	0	84	0	NA	11	86	0	82	0
M-VLDL	88	0	68	35	NA	52	88	0	83	0
S-VLDL	81	0	0	52	NA	63	81	0	79	19
XS-VLDL	0	23	0	73	NA	49	0	23	23	48
IDL	0	36	0	78	NA	44	0	36	23	57
L-LDL	0	43	0	78	NA	64	0	43	20	65
M-LDL	0	51	0	79	NA	63	0	51	32	71
S-LDL	0	53	0	78	NA	71	0	53	40	73
XL-HDL	66	26	88	0	NA	84	66	26	19	0
L-HDL	72	22	83	0	NA	81	72	22	59	28
M-HDL	0	57	0	0	NA	86	0	57	62	58
S-HDL	0	36	0	8	NA	63	0	36	4	50
VLDLd	83	0	26	0	NA	0	83	0	73	0
LDLd	0	25	0	0	NA	50	0	25	0	66
HDLd	75	18	64	32	NA	80	75	18	0	0
Total cholesterol	94	44	71	73	96	73	0	49	92	63
Remnant-c	87	23	0	73	NA	36	87	23	76	52
VLDL-c	89	4	0	61	NA	26	89	4	81	38
LDL-c	91	45	61	71	94	73	0	47	89	66
HDL-c	75	33	90	0	0	68	76	42	73	16
HDL2-c	74	57	70	0	NA	83	74	57	72	34
HDL3-c	0	45	93	43	NA	60	0	45	0	52
Esterified cholesterol	0	56	0	80	NA	77	0	56	0	68
Free cholesterol	43	46	31	77	NA	85	43	46	27	73
ApoA-I	0	55	79	0	NA	88	0	55	0	46
ApoB	86	20	0	73	NA	56	86	20	81	56
Triglycerides	73	0	91	39	48	50	80	0	70	0
Phosphoglycerides	0	48	58	48	NA	91	0	48	0	62
Phosphatidylcholines	0	58	41	62	NA	92	0	58	0	75
Total cholines	0	67	29	73	NA	90	0	67	0	74
Sphingomyelins	30	43	0	85	NA	0	30	43	0	45
DAG	NA	70	NA	0	NA	86	NA	70	NA	84
HDL-TG	0	47	75	44	NA	76	82	0	79	0
VLDL-TG	84	49	60	22	NA	36	84	49	68	40
LDL-TG	82	0	19	68	NA	78	0	47	42	56
TotFA	0	48	5	72	NA	86	0	48	42	68
SFA	0	45	0	65	NA	76	0	45	0	61
MUFA	91	43	91	61	NA	77	91	43	77	55
PUFA	32	64	45	79	NA	89	32	64	0	66
FAw6	10	42	35	77	NA	86	10	42	22	54
LA	0	0	16	70	NA	83	0	0	53	3
FAw3	47	79	13	82	NA	84	47	79	60	80
DHA	0	76	0	64	NA	89	0	76	16	80
CLA	NA	92	NA	0	NA	46	NA	92	NA	93
Glucose	0	54	46	0	57	49	21	51	34	39
HbA1c	62	0	11	0	NA	NA	NA	NA	21	38
Insulin	0	38	0	0	NA	53	0	38	37	0
Lactate	0	0	0	0	NA	0	0	0	0	0
Pyruvate	0	0	0	24	NA	NA	0	0	0	27
Citrate	69	0	0	29	NA	0	69	0	0	0
Glycerol	74	0	83	0	NA	NA	74	0	0	0
Alanine	65	0	62	0	NA	0	65	0	58	0
Glutamine	0	43	0	0	NA	75	0	43	0	58
Glycine	87	0	71	0	NA	NA	87	0	69	55
Isoleucine	0	0	0	0	NA	0	0	0	0	9
Leucine	0	34	0	0	NA	0	0	34	0	52
Valine	45	0	87	0	NA	0	45	0	0	0
Phenilalanine	32	72	30	0	NA	91	32	72	0	79
Tyrosine	0	48	40	0	NA	54	0	48	0	42
Histidine	0	10	0	0	NA	84	0	10	0	0
Acetoacetate	0	0	0	14	NA	NA	0	0	0	0
Acetate	0	31	0	35	NA	64	0	31	74	0
3-OH-butyrate	54	0	0	0	NA	0	54	0	0	0
Albumin	0	11	0	0	NA	0	0	11	0	26
Creatinine	0	61	0	49	NA	85	0	61	22	71
CRP	0	28	81	13	41	0	0	45	0	0
Fibrinogen	16	0	87	0	NA	60	16	0	0	17
IL-6	0	3	69	0	NA	57	0	3	0	0
GlycA	0	43	0	0	NA	39	0	43	58	0
Viscosity	0	56	0	0	NA	NA	0	56	0	0
SBP	0	0	28	11	44	0	0	0	0	0
DBP	68	0	72	36	0	0	83	0	0	0

NA: not applicable (estimates from only one study available). XXL: extremely large, XL: very large, L: large, M: medium, S: small, XS: very small, VLDL: very low-density lipoprotein, LDL: low-density lipoprotein, IDL: intermediate-density lipoprotein, HDL: high-density lipoprotein, c: cholesterol, DAG: diglycerides, TG: triglycerides, TotFA: total fatty acids, SFA: saturated fatty acid, MUFA: monounsaturated fatty acid, PUFA: polyunsaturated fatty acids, FAw6: omega-6 fatty acid, LA: linoleic acid, FAw3: omega-3 fatty acid, DHA: docosaexaenoic acid, CLA: conjugated linoleic acids, HbA1c: glycated haemoglobin, CRP: c-reactive protein, IL-6: interleukin-6, GlycA: glycoprotein acetyls, SBP: systolic blood pressure, DBP: diastolic blood pressure.

Supplementary table 6. P-values for the association of demographic and lifestyle variables with SNPs selected for Mendelian randomization analysis for each participating study

	PEL82	BWHHS	WHII	CaPS	UKCTOCS case-control*	ALSPAC-M
	P-value					
Sex (male vs female)						
rs6810075	0.15	—	0.67	—	—	—
rs16861209	0.12	—	0.45	—	—	—
rs17366568	0.36	—	0.84	—	—	—
rs3774261	0.35	—	0.63	—	—	—
Age (years)						
rs6810075	0.78	0.75	0.28	0.36	0.59	0.001
rs16861209	0.56	0.58	0.27	0.01	0.57	0.83
rs17366568	0.22	0.83	0.47	0.56	0.58	0.93
rs3774261	0.68	0.03	0.96	0.87	0.43	0.15
European (yes vs no)						
rs6810075	0.06	0.50	0.48	—	0.70	0.41
rs16861209	0.75	—	0.12	—	0.16	0.35
rs17366568	0.45	0.61	—	—	0.62	0.19
rs3774261	0.44	0.95	—	—	0.85	—
Smoking (yes vs no)						
rs6810075	0.64	0.22	0.77	0.48	—	0.11
rs16861209	0.57	0.37	0.87	0.48	—	0.24
rs17366568	0.45	0.62	0.44	0.77	—	0.90
rs3774261	0.52	0.08	0.90	0.37	—	0.92
Body mass index (kg/m^2)						
rs6810075	0.63	0.49	0.49	0.21	0.05	0.45
rs16861209	0.39	0.41	0.59	0.65	0.20	0.72
rs17366568	0.47	0.73	0.87	0.11	0.66	0.32
rs3774261	0.48	0.65	0.41	0.44	0.78	0.04

ALSPAC-M: The Avon Longitudinal Study of Children and Parents – mothers' cohort; BWHHS: British Women's Heart and Health Study; CaPS: The Caerphilly Prospective Study; PEL82: 1982 Pelotas Birth Cohort; UKCTOCS: case-control study nested in The United Kingdom Collaborative Trial of Ovarian Cancer Screening; WHII: Whitehall-II Study.