Multiancestry genome-wide association study of lipid levels incorporating gene-alcohol interactions

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A person's lipid profile is influenced by genetic variants and alcohol consumption, but the contribution of interactions between these exposures has not been studied. We therefore incorporated gene-alcohol interactions into a multiancestry genome-wide association study of levels of high-density lipoprotein cholesterol, low-density lipoprotein cholesterol, and triglycerides. We included 45 studies in stage 1 (genome-wide discovery) and 66 studies in stage 2 (focused follow-up), for a total of 394,584 individuals from 5 ancestry groups. Analyses covered the period July 2014–November 2017. Genetic main effects and interaction effects were jointly assessed by means of a 2-degrees-of-freedom (df) test, and a 1-df test was used to assess the interaction effects alone. Variants at 495 loci were at least suggestively associated \( (P < 1 \times 10^{-6}) \) with lipid levels in stage 1 and were evaluated in stage 2, followed by combined analyses of stage 1 and stage 2. In the combined analysis of stages 1 and 2, a total of 147 independent loci were associated with lipid levels at \( P < 5 \times 10^{-8} \) using 2-df tests, of which 18 were novel. No genome-wide-significant associations were found testing the interaction effect alone. The novel loci included several genes (proprotein convertase subtilisin/kexin type 5 (PCSK5), vascular endothelial growth factor B (VEGFB), and apolipoprotein B mRNA editing enzyme, catalytic polypeptide 1 (APOBEC1) complementation factor (A1CF)) that have a putative role in lipid metabolism on the basis of existing evidence from cellular and experimental models.
Serum concentrations of high-density lipoprotein cholesterol (HDL-C), low-density lipoprotein cholesterol (LDL-C), and triglycerides (TG) are modifiable risk factors for cardiovascular disease, the leading cause of death globally (1). Lipid levels are influenced by multiple exposures, including genetic and lifestyle factors. The genetic factors influencing lipid levels have been widely studied (2–8), and large-scale genome-wide association studies (GWAS) have identified 236 loci associated with HDL-C, LDL-C, and TG, which account for up to approximately 12% of the total trait variance in the studied populations (5, 7).

Lifestyle factors, such as alcohol consumption, are also considerably associated with lipid levels: In epidemiologic studies, greater alcohol consumption is associated with an improved lipid profile, including associations with HDL-C levels, high-density lipoprotein particle concentrations, and HDL-C fractions (9, 10). The relationship between alcohol use and LDL-C or TG is less clear, with some studies reporting positive associations while others have reported negative associations (11–20). A causal role of low-to-moderate alcohol consumption in improving overall lipid profile is supported by intervention studies (19), and more recently by Mendelian randomization studies (21, 22).

Potential modification of genetic effects on lipid levels by lifestyle exposures, including alcohol consumption, is relatively unexplored (23). Genetic association studies accounting for potential gene-alcohol interactions may lead to the identification of novel lipid loci and may reveal new biological insights that can potentially be explored for treatment or prevention of dyslipidemia. In order to investigate the potential modulating role of alcohol consumption in the genetic architecture of lipid levels and to identify novel HDL-C, LDL-C, and TG loci, we performed genome-wide gene-alcohol interaction meta-analyses of LDL-C, HDL-C, and TG.

METHODS

Overall design

Table 1 shows the overall design of this study, which was conducted within the setting of the Cohorts for Heart and Aging Research in Genomic Epidemiology (CHARGE) Consortium Gene-Lifestyle Interactions Working Group (24, 25). In order to decrease the computational burden, we carried out genome-wide analyses in stage 1 and followed up suggestively associated variants in stage 2, with the combined results of analyses carried out in stage 1 and stage 2 serving as the primary analysis (26).

We used 2 complementary approaches to model interactions: 1) a 2-degrees-of-freedom (df) test was used to jointly assess both the genetic main effect and the interaction effect on lipid levels, and 2) a 1-df test was used to assess the effect of interactions alone. The 2-df test is more powerful when there is both a genetic main effect and an interaction effect, and it may thus help identify interaction effects for which the 1-df test lacks sufficient power (27).

Overview of participating studies

This analysis covered the period July 2014–November 2017 and included men and women aged 18–80 years from 5 ancestry groups: European, African, Asian, Hispanic, and Brazilian. Investigators in each study obtained informed consent from participants and approval from the appropriate institutional review boards. Although the participating studies are based on different study designs and populations, all of them have data on lipid levels, alcohol consumption, and genotypes across the genome. In total, the analysis comprised 394,584 individuals.

Stage 1 studies. Stage 1 included 89,893 European-ancestry participants, 20,989 African-ancestry participants, 12,450 Asian-ancestry participants, and 3,994 Hispanic-ancestry participants, for an overall total of 127,326 individuals from 45 studies (see Web Table 1, available at https://academic.oup.com/aje; namely, the Age, Gene/Environment Susceptibility (AGES)-Reykjavik Study (1967—Reykjavik, Iceland), the Atherosclerosis Risk in Communities (ARIC) Study (1988–1989—Washington County, Maryland; Forsyth County, North Carolina; Jackson, Mississippi; and Minneapolis, Minnesota), the Coronary Artery Risk Development in Young Adults (CARDIA) Study (1985–1986—Birmingham, Alabama; Chicago, Illinois; Minneapolis, Minnesota; and Oakland, California), the Cardiovascular Health Study (CHS) (1988–1990 and 1992–1993—Forsyth County, North Carolina; Sacramento County, California; Washington County, Maryland; and Pittsburgh, Pennsylvania), the CROATIA-Korcula Study (2007—Korcula, Croatia), the CROATIA-Vis Study (2003–2004—Vis, Croatia), the Erasmus...


Calculation of variance. An additional study not included in stage 1 or stage 2 was used to determine the variance explained by variants at known and new loci: the Airwave Health Monitoring Study (2004–2015—England, Scotland, and Wales, United Kingdom).

Phenotype and lifestyle variables

Three lipid traits were analyzed separately: HDL-C (mg/dL), LDL-C (mg/dL), and TG (mg/dL). HDL-C and TG were directly assayed, while LDL-C was either directly assayed or estimated using the Friedewald equation: LDL-C = TC − HDL-C − (TG/5) (28). Only fasting samples (≥8 hours) were used to assay TG, and the Friedewald equation was only used in samples with fasting TG concentrations less than or equal to 400 mg/dL. LDL-C values were adjusted for use of statins (Web Appendix). HDL-C and TG values were natural log-transformed prior to analyses.

Alcohol consumption was assessed using 2 dichotomized alcohol consumption variables: “current drinking” status, defined as any recurrent drinking behavior, and “regular drinking” status, defined as the subset of current drinkers who consumed at least 2 drinks per week. Because the standard pure ethanol content in 1 alcoholic drink may vary among countries, for this study a standard drink was defined to contain approximately 13 g of pure ethanol, and this measure was used to standardize the definitions across studies.

Genotyping and imputation

Information on genotyping and imputation for each of the stage 1 and stage 2 studies is presented in Web Table 3 and Web Table 4, respectively. For imputation, most studies used the 1000 Genomes Project Phase I Integrated Release Version 3 Haplotypes (2010–2011 data freeze; March 14, 2012, haplotypes), which contain haplotypes for 1,092 individuals from multiple ancestry groups (29).

Study-specific analysis

Study-specific regression analyses were performed for each variant, using models containing the genetic variant, the alcohol consumption variable (current drinking status or regular drinking status), and their interaction. Variants were coded according to the additive model, so that the β coefficient represents the effect size per copy of the coded allele. These regressions were adjusted for age, sex, ancestry-informative principal components, and study-specific variables where appropriate (such as center for multicenter studies). Information on the principal components and study-specific variables adjusted for in each study-specific analysis is provided in Web Tables 3 and 4.

In stage 1, investigators in each study performed genome-wide association analyses within each ancestry group and provided the CHARGE Consortium with information on the estimated genetic main effect, the estimated interaction effect, and a robust estimate of the corresponding covariance matrix. In stage 2, investigators in each study performed analyses only for the selected variants identified in stage 1. Study-specific association analyses were performed using various software programs (Web Appendix and Web Tables 3 and 4). Extensive quality control using the R (R Foundation for Statistical Computing, Vienna, Austria) package “EasyQC” was performed for all study-specific GWAS results, as described in the Web Appendix (30).

Meta-analysis

We implemented METAL software to meta-analyze the genetic main and interaction effects jointly using the 2-df approach of Manning et al. (27) and Willer et al. (31) and to meta-analyze the interaction coefficients alone using inverse-variance–weighted meta-analysis (1-df test). For each meta-analysis, results were obtained from Wald tests, performed using genetic main-effect estimates, interaction effect estimates, and robust estimates of the corresponding covariance matrix. Meta-analyses were performed for each of the 12 analyses (3 lipids × 2 alcohol consumption exposures × 2 tests). Genomic control correction was applied twice (32), first to the study-specific GWAS results (Web Table 5) and then to the ancestry-specific meta-analysis results. The results from each ancestry group were then combined in a transancestry meta-analysis.

The variants that were at least suggestively associated with lipid levels (P < 1 × 10−5) in any of the stage 1 interaction analyses were pursued for stage 2 analysis. In stage 2, we used the same approaches as in stage 1 to perform ancestry-specific and transancestry meta-analyses. Finally, ancestry-specific and transancestry meta-analyses were performed to combine stage 1 results with stage 2 results. Variants with P values less than 5 × 10−8 for either the 2-df joint test of genetic main and interaction effects or the 1-df test of interaction effects were considered genome-wide-significant. False discovery rate (FDR) q values were calculated using the Benjamini and Hochberg method (33) implemented with the “p.adjust” function in R, correcting for the number of tests performed in stage 1. FDR q values less than 0.05 thus indicate a ≤5% FDR even after considering the multiple testing introduced by performing genome-wide analyses on multiple outcomes using multiple models. An independent locus was defined as the ±1 mega–base-pair region surrounding an index variant. For each locus, the closest genes were determined on the basis of proximity to the index variant. For loci with intergenic index variants, we included the closest gene in each direction.

Additional analyses

The percentages of variance in HDL-C, LDL-C, and TG levels explained by all previously known and novel variants
were evaluated in 10 studies on multiple ancestry groups (Web Appendix). The HaploReg (34), RegulomeDB (35), and Genotype-Tissue Expression (GTEx) (36) software packages were used to annotate variants at significant loci. We also used Data-driven Expression Prioritized Integration for Complex Traits (DEPICT) software (37) to prioritize genes at the loci associated with lipid levels in the combined analysis of stages 1 and 2. More details on gene prioritization using DEPICT can be found in the Web Appendix.

Lastly, we examined the associations of index variants at the 147 significant loci with coronary artery disease and myocardial infarction using publicly available summary association results from a large GWAS of these phenotypes performed by the Coronary Artery Disease Genome-Wide Replication and Meta-Analysis (CARDIoGRAM) plus Coronary Artery Disease (C4D) Genetics Consortium (CARDIoGRAMplusC4D Consortium) (38).

RESULTS

Descriptive statistics for the studies participating in stage 1 of the analysis are shown in Web Table 1: 56.1% of stage 1 participants were current drinkers, and 39.9% were regular drinkers. The stage 1 genome-wide analyses identified 25,115 variants in 495 independent loci that were at least suggestively associated ($P < 1 \times 10^{-8}$) with HDL-C, LDL-C, or TG using either the 1-df test of the interaction or the 2-df test that jointly assessed genetic main and interaction effects. The 1-df interaction test identified 356 suggestively associated variants, while the 2-df joint test identified an additional 24,759 variants. Manhattan and quantile-quantile plots are shown in Web Figure 1 and Web Figure 2, respectively.

The 25,115 variants were then evaluated in stage 2. Descriptive statistics for the studies participating in stage 2 are shown in Web Table 2: 58.5% of stage 2 participants were current drinkers, and 41.0% were regular drinkers. The combined analysis of stage 1 and stage 2 findings identified 22,590 variants at 147 independent loci with genome-wide significance ($P < 5 \times 10^{-8}$; Web Table 6). All genome-wide-significant associations were confirmed by the 2-df joint tests of main and interaction effects. There were no genome-wide-significant 1-df interaction associations in the combined analysis of stage 1 and stage 2. At genome-wide significance, 95 of the 147 loci were associated with HDL-C, 66 were associated with LDL-C, and 58 were associated with TG. Of the 147 loci, 60 loci were associated with more than 1 lipid trait, as shown in a Venn diagram in Figure 1.

Novel loci

Of the 147 identified genome-wide-significant loci, 18 are novel lipid loci that have not been previously identified by other association studies for HDL-C, LDL-C, TG, or total cholesterol (Table 2 and Web Figure 3) (2–8). A concurrent genetic association study of exonic variants also identified 4 of these 18 novel loci (39), as indicated in Table 2. Eight of the novel loci involved HDL-C, 8 involved LDL-C, and 7 involved TG, as shown in the heat map in Figure 2. The most significant associations at each of the 18 novel loci all had FDR $q$ values less than 0.05 (Table 2), indicating that they were unlikely to be false-positive findings introduced by multiple testing. As shown in forest plots (Web Figure 4), the 2-df associations at the novel loci were predominantly driven by genetic main effects, with a smaller contribution from interaction effects. Furthermore, of the 18 index variants, 15 had at least suggestively significant ($P < 1 \times 10^{-8}$) genetic main effects in stage 1 (Web Appendix and Web Table 7). None of the associations at the 18 novel loci displayed heterogeneity across ancestry groups (Table 2).

Known loci

The remaining 129 of the 147 significant loci had been identified in previous GWAS of lipid traits (Web Table 6) (2–8). This is a subset of all known lipid loci: Web Table 8 shows the significance of 314 reported index variants in all 236 known lipid loci among all 2-df joint tests and 1-df interaction tests of the combined analysis of stage 1 and stage 2, or stage 1 alone for variants not meeting the stage 2 inclusion criteria (2–8). Considering only the 314 known variants, no 1-df interactions were significant in the European, African, or transancestry meta-analyses ($P < 8.8 \times 10^{-8}$, corresponding to 0.05/(314 variants × 3 lipid traits × 2 alcohol consumption variables × 3 ancestry groups)).

Additional analyses

The percentages of variance in LDL-C, HDL-C, and TG concentrations explained by various loci were calculated in individual studies of multiple ancestry groups. Across ancestry groups, the mean variance explained by known lipid loci was 9.1% for HDL-C, 10.4% for LDL-C, and 7.5% for TG. The total percentage of additional variance explained by the 18 novel loci, including both genetic main effects and interaction effects, was 0.2 for HDL-C, 0.3 for LDL-C, and 0.4 for TG. Ancestry-specific and study-specific estimates are shown in Web Table 9.

Functional annotations using HaploReg (34) and RegulomeDB (35) for variants at the 147 loci that were associated in the combined analysis of stages 1 and 2 are presented in Web Table 10, and associations of these variants with gene expression levels from the GTEx database (36) in a variety of...
### Table 2. Novel Loci Discovered in a Genome-Wide Meta-Analysis of Gene-Alcohol Interaction and Lipid Levels (Combined Analysis of Stages 1 and 2) Using a 2-Degrees-of-Freedom Model That Jointly Tested Main and Interaction Effects, 2017

<table>
<thead>
<tr>
<th>rsID</th>
<th>Chromosome No.:Position</th>
<th>Alleles</th>
<th>Frequency</th>
<th>Closest Gene(s)</th>
<th>Main Effect</th>
<th>Interaction Effect</th>
<th>Joint P Value</th>
<th>Joint FDR q Value</th>
<th>Interaction P Value</th>
<th>Heterogeneity P Value</th>
<th>Most Significant 2-df Model</th>
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<tr>
<td>rs190528931†</td>
<td>11:63911273</td>
<td>A/C</td>
<td>0.04</td>
<td>MACROD1</td>
<td>0.0109</td>
<td>-0.0023</td>
<td>1.9 x 10^-16</td>
<td>3.6 x 10^-11</td>
<td>0.32</td>
<td>0.96</td>
<td>META®—HDL-C—CURDRINK</td>
</tr>
<tr>
<td>rs7904973†</td>
<td>10:124693587</td>
<td>T/G</td>
<td>0.55</td>
<td>C10orf88</td>
<td>0.9200</td>
<td>-0.1500</td>
<td>1.9 x 10^-15</td>
<td>3.5 x 10^-10</td>
<td>0.38</td>
<td>0.89</td>
<td>META—LDL-C—CURDRINK</td>
</tr>
<tr>
<td>rs37320983</td>
<td>7:137559799</td>
<td>C/T</td>
<td>0.91</td>
<td>CREB3L2</td>
<td>4.0100</td>
<td>0.6500</td>
<td>8.2 x 10^-15</td>
<td>1.4 x 10^-9</td>
<td>0.57</td>
<td>0.22</td>
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<tr>
<td>rs80080062</td>
<td>3:185812169</td>
<td>G/C</td>
<td>0.87</td>
<td>ETV5</td>
<td>0.0106</td>
<td>0.0031</td>
<td>1.1 x 10^-12</td>
<td>1.7 x 10^-7</td>
<td>0.38</td>
<td>0.85</td>
<td>META—LDL-C—REGDRINK</td>
</tr>
<tr>
<td>rs7140110</td>
<td>13:114544024</td>
<td>C/T</td>
<td>0.73</td>
<td>GNAS-AS1</td>
<td>-0.0100</td>
<td>-0.0400</td>
<td>3.4 x 10^-12</td>
<td>5.1 x 10^-7</td>
<td>0.19</td>
<td>0.42</td>
<td>META—TG—CURDRINK</td>
</tr>
<tr>
<td>rs34311866</td>
<td>4:951947</td>
<td>C/T</td>
<td>0.83</td>
<td>TMEM175</td>
<td>-0.0200</td>
<td>0.0040</td>
<td>1.5 x 10^-11</td>
<td>2.1 x 10^-6</td>
<td>0.42</td>
<td>0.90</td>
<td>EUR—TG—CURDRINK</td>
</tr>
<tr>
<td>rs2911977</td>
<td>8:6607634</td>
<td>G/C</td>
<td>0.34</td>
<td>AGPAT5</td>
<td>-0.7500</td>
<td>0.0100</td>
<td>7.5 x 10^-11</td>
<td>1.1 x 10^-5</td>
<td>0.53</td>
<td>0.49</td>
<td>META—LDL-C—CURDRINK</td>
</tr>
<tr>
<td>rs56076449</td>
<td>5:132442190</td>
<td>G/T</td>
<td>0.79</td>
<td>HSPA4/FSTL4</td>
<td>0.0130</td>
<td>-0.0020</td>
<td>9.3 x 10^-11</td>
<td>1.3 x 10^-5</td>
<td>0.80</td>
<td>0.80</td>
<td>META—TG—REGDRINK</td>
</tr>
<tr>
<td>rs14724090†</td>
<td>10:52573772</td>
<td>T/C</td>
<td>0.01</td>
<td>A1CF</td>
<td>0.1080</td>
<td>-0.0310</td>
<td>9.6 x 10^-10</td>
<td>1.3 x 10^-4</td>
<td>0.62</td>
<td>1.00</td>
<td>EUR—TG—REGDRINK</td>
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<tr>
<td>rs7035578</td>
<td>9:78745177</td>
<td>A/G</td>
<td>0.15</td>
<td>PCSK5</td>
<td>-1.2700</td>
<td>0.0800</td>
<td>1.2 x 10^-9</td>
<td>1.6 x 10^-4</td>
<td>0.70</td>
<td>0.82</td>
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<tr>
<td>rs201445483</td>
<td>2:17890087</td>
<td>I/D</td>
<td>0.83</td>
<td>SMC6</td>
<td>1.4300</td>
<td>0.6800</td>
<td>4.7 x 10^-9</td>
<td>6.0 x 10^-4</td>
<td>0.17</td>
<td>0.46</td>
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<tr>
<td>rs72729610</td>
<td>4:154190695</td>
<td>G/A</td>
<td>0.86</td>
<td>TRIM2</td>
<td>0.0075</td>
<td>-0.0036</td>
<td>5.6 x 10^-9</td>
<td>7.2 x 10^-4</td>
<td>0.08</td>
<td>0.28</td>
<td>META—HDL-C—REGDRINK</td>
</tr>
<tr>
<td>rs143528679</td>
<td>4:124558378</td>
<td>G/A</td>
<td>0.10</td>
<td>SPRY1/LINC0191</td>
<td>-1.2000</td>
<td>-5.6300</td>
<td>6.3 x 10^-9</td>
<td>8.0 x 10^-4</td>
<td>6.4 x 10^-4</td>
<td>0.10</td>
<td>AFR—LDL-C—CURDRINK</td>
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<tr>
<td>rs2111622†</td>
<td>5:23984838</td>
<td>G/A</td>
<td>0.77</td>
<td>ASB3/GPR75-ASB3</td>
<td>0.0008</td>
<td>-0.0072</td>
<td>7.9 x 10^-9</td>
<td>9.9 x 10^-4</td>
<td>0.01</td>
<td>0.12</td>
<td>EUR—LDL-C—CURDRINK</td>
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<tr>
<td>rs13284665</td>
<td>9:131513370</td>
<td>G/A</td>
<td>0.88</td>
<td>ZER1</td>
<td>1.9900</td>
<td>-0.8900</td>
<td>1.1 x 10^-8</td>
<td>1.3 x 10^-3</td>
<td>0.35</td>
<td>0.89</td>
<td>EUR—LDL-C—CURDRINK</td>
</tr>
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<td>rs4898521</td>
<td>12:49755162</td>
<td>A/T</td>
<td>0.95</td>
<td>DNAJ2/C2/SPATS2</td>
<td>0.0179</td>
<td>-0.0107</td>
<td>1.3 x 10^-8</td>
<td>1.7 x 10^-3</td>
<td>0.06</td>
<td>1.00</td>
<td>EUR—HDL-C—REGDRINK</td>
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<tr>
<td>rs0663050</td>
<td>20:45604240</td>
<td>C/T</td>
<td>0.75</td>
<td>EYA2</td>
<td>0.0110</td>
<td>0.0000</td>
<td>2.9 x 10^-8</td>
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<td>0.30</td>
<td>0.39</td>
<td>META—TG—CURDRINK</td>
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<tr>
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<td>4.2 x 10^-3</td>
<td>0.96</td>
<td>0.23</td>
<td>EUR—TG—REGDRINK</td>
</tr>
</tbody>
</table>

Abbreviations: A1CF, APOBEC1 complementation factor gene; ADP, adenosine diphosphate; AFR, African ancestry; AGPAT5, 1-acetylglcerol-3-phosphate O-acetyltransferase 5 gene; APOBEC1, apolipoprotein B mRNA editing enzyme, catalytic polypeptide 1; AS1, antisense RNA 1 gene; ASB3, ankryin repeat and SOCS box containing 3 gene; CAMP, cyclic adenosine 3’,5’-monophosphate; C10orf88, chromosome 10 open reading frame 88 gene; CREB3L2, CAMP response element binding protein 3 like 2 gene; CURDRINK, current drinkers; df, degrees of freedom; DNAJC22, DnaJ heat shock protein family (Hsp40) member C22 gene; EBF, early B cell factor; EBF1, EBF transcription factor 1 gene; ETS, E26 transformation-specific; ETV5, ETS variant 5 gene; EUR, European ancestry; EYA, eyes absent; EYA2, EYA transcriptional coactivator and phosphatase 2 gene; FDR, false discovery rate; FSTL4, follistatin like 4 gene; GAS6, growth arrest specific 6 gene; GPR75, G protein-coupled receptor 75 gene; HDL-C, high-density lipoprotein cholesterol; Hsp, heat shock protein; HSPA4, heat shock protein family a (Hsp70) member 4 gene; LDL-C, low-density lipoprotein cholesterol; LINC0191, long intergenic non-protein coding RNA 1091 gene; LOC101927697, uncharacterized locus 101927697; MACROD1, macro domain-containing protein 1 gene; META, meta-analysis; PCSK5, proprotein convertase subtilisin/kexin type 5 gene; REGDRINK, regular drinkers; rsID, reference SNP identifier; RTK, receptor tyrosine kinase; SMC6, structural maintenance of chromosomes 6 gene; SNP, single nucleotide polymorphism; SOCS, suppressor of cytokine signaling; SPATS2, spermatogenesis associated serine rich 2 gene; SPRY1, sprouty RTK signaling antagonist 1 gene; TG, triglycerides; TMEM175, transmembrane protein 175 gene; TRIM2, tripartite motif containing 2 gene; ZER1, Zyg-11 related cell cycle regulator gene.

† Coded allele/non-coded allele.
‡ Frequency of the coded allele.
§ These estimates pertain to the 2-df joint test of main and interaction effects.
¶ These P values pertain to 1-df tests of interaction effects.
‖ Significance of the stage 1 heterogeneity across ancestry groups in the most significant 2-df model.
¶¶ These loci were also discovered by Liu et al. (39) in a concurrent association study focused on exonic variants.
|| Trans-ancestry meta-analysis.
° Alcohol consumption categorized into drinkers and nondrinkers.
** Alcohol consumption categorized into regular drinkers and non–regular drinkers.
tissues are shown in Web Table 11. A total of 443 variants were associated with gene expression levels, of which 27 variants were indicated by RegulomeDB as having strong evidence for an association with enhancer function.

Our gene prioritization analyses with DEPICT highlighted (FDR q values <5%) 165 genes at HDL-C-associated loci, 110 genes at LDL-C-associated loci, and 87 genes at TG-associated loci (Web Tables 11–14). Thus, at some loci, multiple potential causal genes were prioritized. DEPICT identified 656, 877, and 497 reconstituted gene sets that were significantly enriched (FDR q values <5%) for genes at HDL-C, LDL-C, and TG loci, respectively (Web Table 15). This large number of processes and enriched gene sets underscores the complex genetic, biological, and physiological mechanisms underlying lipid traits. Among the most significantly enriched gene sets were processes related to “total amount of body fat” and “abnormal liver morphology.” Finally, DEPICT revealed that genes at associated HDL-C, LDL-C, or TG loci were significantly enriched (FDR q values <5%) for association with gene expression in 23 tissues, 14 cell types, and 12 physiological systems (Web Table 16). We found a compelling enrichment of genes acting in hepatocytes and liver processes at associated loci for each of the 3 traits and of genes acting in adipose tissues for HDL-C and TG loci (Web Table 16, Web Figure 5).

Fourteen index variants at known lipid loci were associated with coronary artery disease with \( P \) values less than \( 1.7 \times 10^{-4} \) (0.05/(147 variants \( \times \) 2 disease outcomes)), and 11 of these were also associated with myocardial infarction (Web Table 17) (38). None of the index variants at novel loci were significantly associated with these clinical endpoints.

**DISCUSSION**

We performed a GWAS of lipid levels incorporating interactions with alcohol consumption and identified 147 genomewide-significant lipid loci, of which 18 are novel.

Despite the large sample of 394,584 individuals, which is comparable to sample sizes in other successful genetic interaction studies (40, 41), genome-wide-significant interactions were not found in the present study. Gene-alcohol interactions also do not appear to have contributed substantially to the discovery of the 18 novel loci, given that the genetic main effect of index variants at 15 of the 18 novel loci passed the stage 1 suggestive significance threshold. Below, we highlight 3 of the novel loci that harbor especially promising candidate genes with putative roles in lipid metabolism based on existing evidence from cellular and experimental models.

One of the newly identified associations for LDL-C maps to the proprotein convertase subtilisin/kexin type 5 gene (PCSK5), a member of the same gene family as proprotein convertase subtilisin/kexin type 9 (PCSK9), which is targeted by new drugs that successfully lower LDL-C levels (42, 43). Several independent lines of evidence support the involvement of PCSK5 in the regulation of lipid levels. First, in a candidate gene study, Iatan et al. (44) found that variants in PCSK5 were associated with levels of HDL-C. Additionally, in vitro studies of cell lines show that proprotein convertase subtilisin/kexin type 5 (PCSK5) inactivates endothelial lipase directly through cleavage and that it may also inactivate endothelial lipase and lipoprotein lipase indirectly through activation of angiopoietin-like protein 3 (45). Endothelial lipase, lipoprotein lipase, and angiopoietin-like protein 3 have all been robustly implicated in the regulation of lipid levels, probably with primary roles in the metabolism of HDL-C and TG (3, 46–48). In our study, the PCSK5 locus was associated at genome-wide significance only with LDL-C levels; it was associated at nominal significance \( (P < 0.05) \) with TG levels.

One novel locus for TG mapped to the apolipoprotein B mRNA editing enzyme, catalytic polypeptide 1 (APOBEC1) complementation factor gene (A1CF), which encodes APOBEC1 complementation factor. Liu et al. (39) also identified the same index variant (rs41274050) in association with TG in a concurrent study. They showed that introducing the minor allele of rs41274050 in mice led to increased TG levels, confirming the functional role of this missense variant in the regulation of TG levels (39). APOBEC1 complementation factor forms an enzymatic complex with APOBEC1 and deaminates apolipoprotein B mRNA (49). This site-specific deamination of cytidine to uridine results in the production of the apolipoprotein B 48 isoform as opposed to the apolipoprotein B 100 isoform (49). The apolipoprotein B 48 isoform is critical in the assembly and secretion of chylomicrons, which mainly carry dietary-derived TG (50). Interestingly, a recent GWAS carried out among persons of East Asian ancestry identified the apolipoprotein B mRNA editing enzyme, catalytic polypeptide 1 (APOBEC1) locus as being associated with HDL-C levels (5)—an association that we confirmed in our analysis (index variant: 12:7725904:ID). At nominal significance, both of the index variants near A1CF and APOBEC1 were associated with all 3 lipid traits \( (P < 0.05) \). Given the role of apolipoprotein B 100 in atherosclerosis, promoting the synthesis of apolipoprotein B 48 instead of apolipoprotein B 100 may represent a possible therapeutic strategy for the prevention of cardiovascular disease (51). Neither the index variant at A1CF nor APOBEC1 was significantly associated with coronary artery disease or myocardial infarction in the largest GWAS of these outcomes. However, further studies are needed to characterize their role in cardiovascular disease, given our multiancestry design and the European-driven design of the available GWAS data on cardiovascular disease outcomes (Web Table 17).

Variants closest to the mono-ADP ribosylhydrolase 1 (macro domain-containing protein 1) gene (MACRODI) were associated with HDL-C levels and TG levels. This locus was also reported in the concurrent study by Liu et al. (39), although the index variant in their study was located in the phospholipase C beta 3 (PLCB3) gene, around 120 kilobase-pairs away from the index variant in the present study. We found that variants at this locus were associated with expression levels of another nearby gene, the vascular endothelial growth factor B gene (VEGFB), in adipose and heart tissue (Web Table 11). Vascular endothelial growth factor B (VEGF-B) is reportedly involved in endothelial fatty acid transport, with Vegenf−/− mice showing less accumulation of lipids in muscle, heart, and brown adipose tissue but a greater uptake of fatty acids in white adipose tissue and higher body weight (52). Additionally, inhibition of the vascular endothelial growth factor B (Vegfb) protein in a mouse model of type 2 diabetes resulted in an improved glycemic profile, as well as a reduction of dyslipidemia (53). Mice lacking...
the Vegfb protein had lower levels of TG and LDL-C accompanied by higher levels of HDL-C. Subsequent studies in other mouse models did not corroborate these findings: Dijkstra et al. found in an independent strain of mice that knocking out the mouse vascular endothelial growth factor B gene (Vegfb) had no effect on TG and total cholesterol levels, while Rubciuc et al. and Raffi and Carmeliet reported that transduction of the human VEGFB gene into mice led to increased vascularity in adipose tissue and an improved lipid profile. Our results provide insight into the effects of VEGF-B in humans to complement the divergent reports from rodent studies. The A allele of index variant rs190528931 is associated with decreased expression of VEGFB in adipose and heart tissue, decreased levels of HDL-C, and increased levels of TG. Additionally, rs190528931 was also associated with nominally significant increased levels of LDL-C ($P < 0.05$). Hence, evidence from our study suggests that inhibition of VEGF-B does not improve lipid profile but instead promotes dyslipidemia.

The strengths of this study include the large sample size, the diverse ancestral composition of the sample, and the use of a dense reference panel for genotype imputation (57). A limitation of this study is the imbalance in ancestry groups between stage 1 and stage 2. Persons of African ancestry were well-represented in stage 1 but underrepresented in stage 2. In contrast, persons of Asian and Hispanic ancestry were relatively underrepresented in stage 1 as compared with stage 2. A more balanced division of participants across stages 1 and 2 may have led to the identification of additional loci. Additionally, alcohol consumption may be underreported in both self-administered questionnaires and interviews, leading to a loss of statistical power due to misclassification (58). Similarly, the classification of alcohol consumption into categories such as “regular drinkers” and “current drinkers” may have reduced power relative to treating it as a fully quantitative variable (59). Nevertheless, the use of such categories was necessary for harmonizing data from 111 studies with heterogeneous measurement of alcohol consumption. It is plausible that more
comprehensive characterization of alcohol consumption could reveal interactions that were missed in our study.

In conclusion, we identified 18 novel loci that were significantly associated with lipid traits, and these include several loci with genes (PCSK5, VEGFB, and A1CF) that have a putative role in lipid metabolism based on existing evidence from cellular and experimental models. The associations identified in this study appear to be driven by genetic main effects, and it remains uncertain whether alcohol consumption modifies the association of genetic variants with lipid levels.

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