SHORT REPORT

Meta-analysis of 49,549 individuals imputed with the 1000 Genomes Project reveals an exonic damaging variant in ANGPTL4 determining fasting TG levels

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ABSTRACT

Background So far, more than 170 loci have been associated with circulating lipid levels through genome-wide association studies (GWAS). These associations are largely driven by common variants, their function is often not known, and many are likely to be markers for the causal variants. In this study we aimed to identify more new rare and low-frequency functional variants associated with circulating lipid levels.

Methods We used the 1000 Genomes Project as a reference panel for the imputations of GWAS data from ~60,000 individuals in the discovery stage and ~90,000 samples in the replication stage.

Results Our study resulted in the identification of five new associations with circulating lipid levels at four loci.

Conclusions This study illustrates that GWAS with high-scale imputation may still help us unravel the biological mechanism behind circulating lipid levels.

INTRODUCTION

Genome-wide association studies (GWAS) for circulating lipid levels (high-density lipoprotein cholesterol (HDL-C), low-density lipoprotein cholesterol (LDL-C), total cholesterol (TC) and triglycerides (TG)) have identified over 170 loci. These...
studies have been based on imputations to the HapMap reference panel or primary versions of the 1000 Genomes Project (1kG) or genotyping on the Illumina Exome Chip. None has used imputations with the Phase 1 integrated release v3 of the 1kG which allows the imputation of rare and low-frequency functional variants associated with circulating lipid levels comes from recent studies in which exome sequencing of the NPC1L1 gene identified rare variants associated with reduced LDL-C levels and reduced risk of coronary heart disease. Moreover, exome sequencing of LDLR and APOA5 identified rare variants associated with an increased LDL-C and increased TG levels and exome sequencing of APOC3 identified rare variants associated with reduced TG levels and reduced risk of coronary heart disease.

Our goal in this study was to identify rare and low-frequency functional variants associated with circulating lipid levels in a larger sample size compared with the exome sequencing of candidate gene approach. To this end, we imputed genotypes for study samples participating in the cohorts of the Cohorts for Heart and Aging Research in Genomic Epidemiology (CHARGE) consortium using the Phase 1 integrated release V.3 of the 1kG and conducted a meta-analysis of about approximately 60,000 individuals, followed by a replication in an independent set of 90,000 individuals.

METHODS

Please see online supplementary methods for complete descriptions of the methods. In summary, for the discovery stage of this project, we used the data from 20 cohorts of the CHARGE consortium (see online supplementary methods). All cohorts were imputed with reference to the 1kG reference panel (version Phase 1 integrated release V3). The total number of individuals in the discovery stage was 59,409 for HDL-C, 48,780 for LDL-C, 60,024 for TC and 49,549 for TG. Online supplementary tables S1 and S2 contain the baseline characteristics per cohort and more details about SNP genotyping and genotype imputations. Within each cohort, each variant was tested for association with each of the lipid traits, assuming an additive genetic model. The association results of all cohorts for all variants were combined using inverse variance weighting. We used the following filters for the variants: 0.3<\(R^2\) (measurement for the imputation quality) ≤1.0 and expected minor allele count (expMAC=\(2\times MAF\) (minor allele frequency))\(\times R^2\times\)sample size) >10 prior to meta-analysis. After meta-analysis of all available variants, we excluded the variants that were not present in at least four cohorts, to prevent false positive findings. In order to select only variants that were independently associated with each of the lipid traits, we used the genome-wide complex trait analysis (GCTA) tool, V1.13. To identify novel loci we selected from the list of variants identified by GCTA, those variants which are within 0.5 Mb of a loci previously published by Teslovich et al or GLGC, which resulted in three variants for HDL-C, three for LDL-C, seven for TC and six for TG. These variants are located at 17 different loci and include one deletion (figure S1 and table 1).

These 19 variants were selected for replication. The total number of individuals in the replication stage was 84,598, 72,486, 83,739 and 73,519 for HDL-C, LDL-C, TC and TG, respectively (see online supplementary tables S1 and S2 for baseline characteristics and information about SNP genotyping and imputation details). The sample size in the replication stage was larger than the initial discovery sample for 17 out of the 19 variants. The frequencies of the variants were similar between the discovery and replication cohorts. The directions of effect were the same in the discovery and replication cohorts for 16 out of the 19 variants (see online supplementary figure S7). We used a Bonferroni corrected threshold for significance (p value<2.63\(\times 10^{-8}\)). Five out of the 19 variants were significantly replicated (table 1): rs6457374 (TC), rs186696265 (LDL-C and TC), rs77697917 (HDL-C) and rs116843064 (TG). The frequency of these variants ranged between 0.012 and 0.249 within the replication sample. Online supplementary table S5 shows the heterogeneity for the 19 variants after the meta-analysis of all discovery cohorts and of all replication cohorts. We also meta-analysed all variants in the individuals of the discovery cohorts and replication cohorts combined (table 1 and see online supplementary tables S5 and S6) and per ethnicity (see online supplementary table S6) using a fixed-effect meta-analysis approach. We found that the five significantly replicated variants we identified in this study are only significant within the European samples, thereby noticing that there are much more European samples in this study, compared with the African and Asian samples. When using a random-effect meta-analysis to account for the multiple ethnicities in our sample (see online supplementary table S7), we found that the five replicated variants, one attained genome-wide significance (p value<5\(\times 10^{-8}\)) and the other four nominal significance (p value<0.05).

DISCUSSION

We conducted a GWAS that included GWAS data imputed to the 1kG to identify rare and low-frequency, potentially functional, variants associated with circulating lipid levels. To this end, we imputed genotypes in approximately 60,000 individuals from 20 cohorts in the CHARGE consortium with the 1kG
binding cassette (ABC) transporters (p value of $4.29 \times 10^{-5}$) on chromosome 6 between the genes $\text{HLA-C}$ and $\text{HLA-B}$ (figure 2A). Both genes are associated with the KEGG term ATP binding cassette (ABC) transporters (p value of $4.29 \times 10^{-5}$ and $3.84 \times 10^{-5}$ for $\text{HLA-C}$ and $\text{HLA-B}$, respectively, genenetwork.nl). $\text{ANGPTL4}$ has been associated with HDL-C before using the GWAS approach and with TG before using an exome sequencing approach and function of the protein by Polyphen2,8 MutationTaster9 and likelihood ratio test (LRT).10 This amino acid polymorphism has been associated in high linkage disequilibrium (D’=0.936) in the 1 kG with rs72836561, an exonic variant in the gene $\text{CD300LG}$ (MAF=0.027, $p=2.437$, $\text{se}=0.381$, p value=$1.51 \times 10^{-10}$ in the discovery stage). This missense variant changes the amino acid arginine into cysteine (Arg82Cys) and is predicted to be damaging for the structure and function of the protein by Polyphen2,8 MutationTaster9 and LRT.10 This amino acid polymorphism has been associated with HDL-C in exome-wide association studies19 and TG in GWAS1 before.

The fourth variant we identified is rs186696265, which is located on chromosome 6 and associated with LDL-C and TC (figure 2D, E). This intergenic variant is between the $\text{LPA}$ (Lipoprotein, Lp(A)) gene and the $\text{PLG}$ (Plasminogen) gene. The $\text{LPA}$ gene has been associated before with LDL-C and TC before.2 The reported lead SNP was rs1564348, which in the newer human genome versions is annotated to the $\text{SLC22A1}$ (Solute Carrier Family 22 (Organic Cation Transporter), Member 1) gene instead of the $\text{LPA}$ gene, which has been identified by others as well.1

Fourteen out of the 19 variants were not replicated despite similar sample sizes and similar frequencies within the replication stage as compared with the discovery stage. Of those 14 variants, 11 exhibited effect sizes in the same direction in both stages. A possible explanation might be that the replication sample size is much larger compared with that of the discovery sample size. Two variants might have lacked significant replication due to small sample size, rs60839105 and rs151198427.
Table 1  The results for the 19 variants after the meta-analysis of all discovery cohorts, all replication cohorts and all cohorts combined

| Trait | Chr:Position | rs identifier | nearest gene | A1/A2 | Discovery cohorts | | Replication cohorts | | All cohorts combined |
|-------|--------------|---------------|--------------|-------|------------------|-------|------------------|-------|
|       |              |               |              |       | Freq | N | β | SE | p Value | Freq | N | β | SE | p Value | Freq | N | β | SE | p Value |
| HDL-C | 3:72 067 255 | rs75909755 | PROL2-EIF4E3 | T/C | 0.03 | 62 607 | 1.593 | 0.275 | 7.27E-09 | 0.03 | 86 252 | −0.019 | 0.031 | 5.45E-01 | 0.03 | 0.002 | 0.031 | 9.57E-01 |
| TC    | 6:31 272 261 | rs6457374 | HLA-B | T/C | 0.75 | 46 839 | 2.339 | 0.339 | 5.32E-12 | 0.81 | 74 417 | −0.057 | 0.016 | 4.23E-04 | 0.81 | 0.062 | 0.016 | 1.18E-04 |
| LDL-C | 6:31 325 323 | rs9266229 | HLA-B | C/G | 0.53 | 37 981 | −2.201 | 0.344 | 6.16E-10 | 0.41 | 61 582 | −0.025 | 0.014 | 7.37E-02 | 0.41 | −0.029 | 0.014 | 4.04E-02 |
| TG    | 6:36 648 275 | – | CDKN1A | CAG/C | 0.45 | 53 425 | −0.019 | 0.003 | 7.63E-09 | 0.49 | 73 512 | −0.008 | 0.003 | 5.20E-01 | 0.46 | −0.013 | 0.003 | 5.93E-07 |
| HDL-C | 6:31 325 323 | rs6457374 | HLA-B | T/C | 0.81 | 74 417 | 0.057 | 0.016 | 4.23E-04 | 0.81 | 0.062 | 0.016 | 1.18E-04 |
| TC    | 6:31 325 323 | rs6457374 | HLA-B | T/C | 0.81 | 74 417 | 0.057 | 0.016 | 4.23E-04 | 0.81 | 0.062 | 0.016 | 1.18E-04 |
| LDL-C | 6:31 325 323 | rs6457374 | HLA-B | T/C | 0.81 | 74 417 | 0.057 | 0.016 | 4.23E-04 | 0.81 | 0.062 | 0.016 | 1.18E-04 |
| TG    | 6:36 648 275 | – | CDKN1A | CAG/C | 0.45 | 53 425 | −0.019 | 0.003 | 7.63E-09 | 0.49 | 73 512 | −0.008 | 0.003 | 5.20E-01 | 0.46 | −0.013 | 0.003 | 5.93E-07 |
| HDL-C | 7:80 492 357 | rs60839105 | SEMA3C | T/C | 0.07 | 7882 | 3.355 | 0.571 | 4.26E-09 | 0.08 | 4971 | 1.067 | 1.228 | 3.85E-01 | 0.07 | 2.948 | 0.518 | 1.25E-08 |
| TC    | 8:68 351 787 | rs151198427 | CPAP | A/G | 0.13 | 1419 | −2.858 | 2.396 | 2.33E-01 | 0.11 | 4.797 | 1.035 | 3.56E-06 |
| LDL-C | 9:78 728 065 | rs146369471 | PCSK5 | T/C | 0.99 | 51 367 | 0.068 | 0.103 | 5.11E-01 | 0.99 | 0.110 | 0.103 | 2.84E-01 |
| TG    | 9:78 728 065 | rs146369471 | PCSK5 | T/C | 0.99 | 70 241 | 0.015 | 0.003 | 8.84E-01 | 0.99 | 0.057 | 0.003 | 5.79E-01 |
| TC    | 12:51 207 704 | rs829112 | ATFI | A/G | 0.73 | 67 843 | 0.222 | 0.036 | 4.27E-11 | 0.72 | 0.024 | 0.013 | 3.18E-01 |
| TG    | 13:11 454 402 | rs7140110 | GASG | T/C | 0.71 | 42 211 | −0.021 | 0.004 | 3.65E-08 | 0.70 | 437 | −0.006 | 0.005 | 2.68E-01 | 0.72 | −0.015 | 0.003 | 5.13E-07 |
| TG    | 13:11 454 402 | rs7140110 | GASG | T/C | 0.71 | 42 211 | −0.021 | 0.004 | 3.65E-08 | 0.70 | 437 | −0.006 | 0.005 | 2.68E-01 | 0.72 | −0.015 | 0.003 | 5.13E-07 |
| TG    | 15:43 365 025 | rs10509625 | MYO15A | T/C | 0.97 | 45 052 | −2.717 | 0.407 | 2.38E-11 | 0.93 | 67 843 | −0.222 | 0.036 | 4.27E-10 | 0.93 | −0.241 | 0.035 | 1.04E-11 |
| TC    | 17:18 046 290 | rs8065026 | MYO15A | T/C | 0.79 | 76 502 | 1.310 | 1.468 | 4.63E-09 | 0.81 | 76 412 | 0.013 | 0.003 | 4.28E-01 | 0.81 | 0.029 | 0.003 | 2.66E-02 |
| HDL-C | 17:41 840 849 | rs77697917 | SOST-DUSP3 | T/C | 0.02 | 48 221 | −0.021 | 0.004 | 3.65E-08 | 0.01 | 46 221 | −0.006 | 0.005 | 2.68E-01 | 0.02 | −0.015 | 0.003 | 5.13E-07 |
| TG    | 19:8 429 323 | rs116430364 | ANGPTL4 | A/G | 0.03 | 34 643 | −0.101 | 0.016 | 6.46E-11 | 0.03 | 44 194 | −0.065 | 0.019 | 4.53E-04 | 0.03 | −0.087 | 0.012 | 3.83E-13 |
| TC    | 20:22 048 848 | rs2618566 | BANF2-SNX5 | T/G | 0.65 | 63 300 | −1.566 | 0.251 | 4.68E-10 | 0.60 | 88 946 | −0.024 | 0.011 | 2.83E-02 | 0.60 | −0.027 | 0.011 | 1.38E-02 |

The variants in bold are the significantly replicated variants. A1 is allele 1 and A2 is allele 2, Freq is the frequency of A1, β is the effect of A1. HDL-C, high-density lipoprotein cholesterol; LDL-C, low-density lipoprotein cholesterol; TC, total cholesterol; TG, triglycerides.

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Both variants only pass quality control in the cohorts in the discovery stage that contain individuals of African ancestry (see online supplementary figure S7). Although there are several cohorts with individuals of African ancestry in the replication stage, both variants did not pass quality control in most cohorts which leads to the conclusion that these variants might be population-specific. This is also suggested by the 1 kG data (Phase 3) as the frequency of the C-allele is 92% in African samples and 100% in the European samples for rs60839105 and the frequency of the G-allele is 86% in the African samples and 100% in the European samples for rs151198427. Imputations of cohorts with individuals of African ancestry with the African Genome Variation Project20 might confirm the association of rs60839105 with HDL-C and rs151198427 with TC.

To our knowledge, this is the first GWAS of circulating lipid levels using the Phase 1 integrated release V3 of the 1 kG, therefore we cannot compare the positive replication rate with other studies. However, we did replicate 88.1% of the findings of Teslovich et al2 and 43.4% of the findings of GLGC3 despite our smaller sample. A high replication rate is expected based on the high overlap of our samples with the samples of Teslovich et al2 and with the samples of GLGC3 though it indicates that when using the 1000 Genomes instead of the HapMap reference panel, we can achieve a high replication rate using a smaller sample size. We also tried to replicate findings from

Figure 2  The regional association results of the initial meta-analysis of all discovery cohorts for (A) TC on chromosome 6, (B) HDL-C on chromosome 17, (C) TG on chromosome 19, (D) LDL-C on chromosome 6 and (E) TC on chromosome 6. HDL-C, high-density lipoprotein cholesterol; LDL-C, low-density lipoprotein cholesterol; TC, total cholesterol; TG, triglycerides.
exome sequencing of candidate genes. The p.Arg406X mutation in the NPC1LI1 gene (rs145297799), which was reported to be associated with reduced LDL-C levels and reduced risk of coronary heart disease, is not available in the 1kg reference panel and, therefore, we were not able to replicate this finding. Do et al described the exome sequencing of the genes LDLR and APOA5 and identified rare variants associated with an increased risk of myocardial infarction, increased LDL-C and TG levels. Of those rare variants, only two in the LDLR gene and seven in the APOA5 gene exist in our discovery meta-analysis. Both LDLR variants are associated with TG in our discovery meta-analysis (rs34282181, $\beta=-0.093$, SE=0.023, p value=$4.827\times10^{-3}$ and rs2075291, $\beta=0.219$, SE=0.046, p value=$2.092\times10^{-5}$), but not significantly associated with LDL-C (rs34282181, $\beta=-3.939$, SE=1.861, p value=0.034 and rs2075291, $\beta=-2.316$, SE=3.001, p value=0.440). None of the seven APOA5 variants were significantly associated with TG or LDL-C in our discovery meta-analysis (lowest p value is for LDL-C with rs72658860, $\beta=-18.430$, SE=7.140, p value=$9.848\times10^{-6}$). The third published finding we tried to replicate, was the association between APOC3 and TG levels. Of the seven variants reported, only one existed in our discovery meta-analysis (chromosome 11, position 116 701 354), which is associated with TG ($\beta=-0.343$, SE=0.011, p value=$2.311\times10^{-5}$). Those authors also reported an association between a APOA5 variant (rs3135506) and TG as the most significant finding. This variant was also significantly associated with TG in our discovery meta-analysis ($\beta=0.129$, SE=0.007, p value=$1.099\times10^{-8}$). These replication efforts demonstrate that many of the published results of exome sequencing can be replicated through the use of 1 kg imputations.

In conclusion, we identified and replicated five variants associated with circulating lipid levels. These variants are in genes that can be linked biologically to lipid metabolism. Although there were a large number of variants that did not replicate at the accepted genome-wide significance threshold, the low-cost, hypothesis-free approach that we applied uncovered five variants. This study, therefore, illustrates that GWAS may still help us unravel the biological mechanisms behind circulating lipid levels.

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Patient consent for blood lipids.

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