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## 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.

All four loci are within genes that can be linked biologically to lipid metabolism. One of the variants, rs116843064, is a damaging missense variant within the *ANGPTL4* gene.

**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.<sup>1–3</sup> These

studies have been based on imputations to the HapMap reference panel<sup>2</sup> or primary versions of the 1000 Genomes Project (1kG)<sup>1</sup> or genotyping on the Illumina Exome Chip.<sup>3</sup> 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 and structural variations with more precision. Evidence 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.<sup>4</sup> Moreover, exome sequencing of *LDLR* and *APOA5* identified rare variants associated with an increased LDL-C and increased TG levels<sup>5</sup> and exome sequencing of *APOC3* identified rare variants associated with reduced TG levels and reduced risk of coronary heart disease.<sup>6</sup>

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)  $\leq 1.0$  and expected minor allele count ( $\text{expMAC} = 2 \times \text{MAF}$  (minor allele frequency)  $\times R^2 \times \text{sample size}$ )  $> 10$  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)<sup>7</sup> tool, V1.13. To identify novel loci we selected from the list of variants identified by GCTA, those variants located more than 0.5 Mb away from previously identified loci of the corresponding trait<sup>2,3</sup> and which were significant ( $p \text{ value} < 5 \times 10^{-8}$ ) in the initial discovery stage. To prevent the identification of false positive loci, we added a second replication stage within 23 independent cohorts. The experiment-wide significance threshold required to keep type I error rate within the replication stage at 5% is  $2.63 \times 10^{-3}$  (Bonferroni correction based on 19 variants). We also meta-analysed the individuals of the discovery and replication stage together and per ethnicity using a fixed-effect approach. We also repeated this analysis with genome-wide association meta analysis (GWAMA) (V2.0.5) using a random effect approach as the individuals in discovery and replication stages come from multiple ethnicities.

## RESULTS

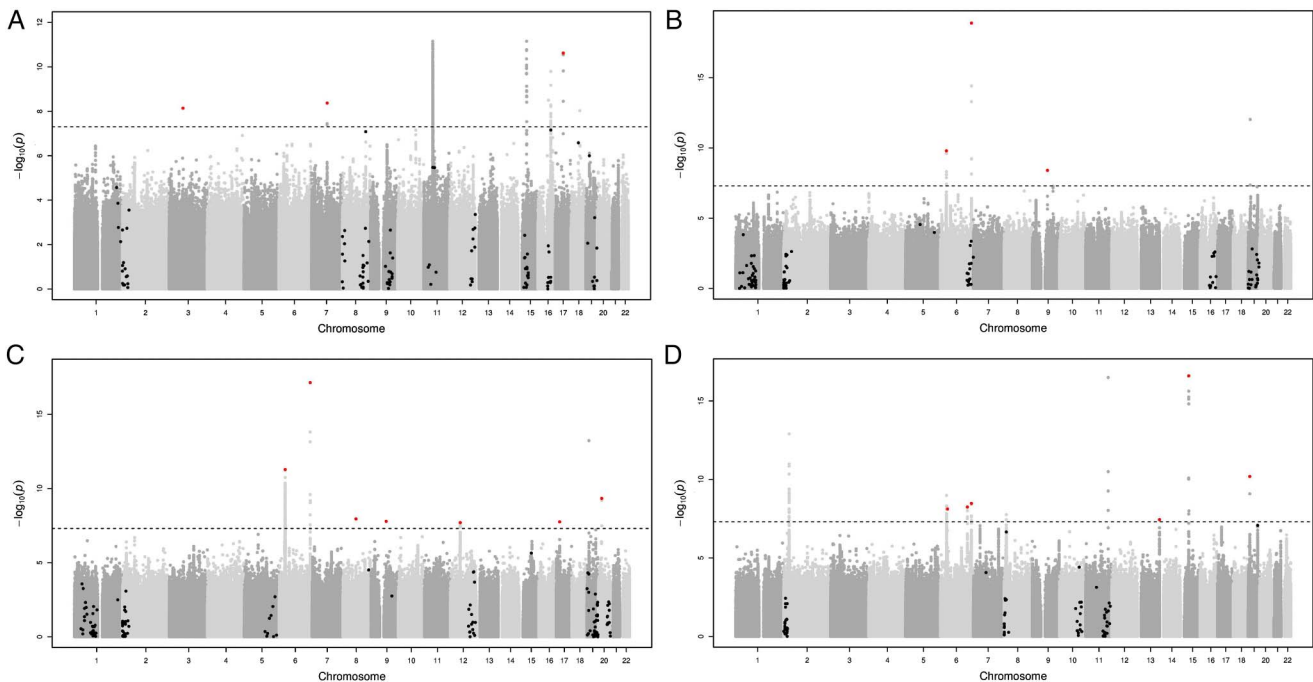
The association of all variants with HDL-C, LDL-C, TC and TG was tested in all discovery cohorts (see online supplementary figures S1 and S2). The association results of all discovery cohorts for all variants were combined in a fixed-effect meta-analysis using METAL (see online supplementary figures S3 and S4). We significantly replicated 88.1% of the loci described by Teslovich *et al*<sup>2</sup> despite a sample size of about 80% (see online supplementary figure S5 and supplementary table S3). We also significantly replicated 43.4% of the loci described by the Global Lipids Genetics Consortium (GLGC)<sup>3</sup> despite a sample size of about 30% (see online supplementary figure S6 and supplementary table S4).

A conditional and joint analysis using GCTA identified 185 independent variants for HDL-C, 174 for LDL-C, 214 for TC and 119 for TG. Next, we excluded all variants that were not genome-wide significant ( $p \text{ value} < 5 \times 10^{-8}$ ) in the initial discovery stage, which resulted in 56 variants for HDL-C, 50 for LDL-C, 66 for TC and 37 for TG. And we excluded all variants which are within 0.5 Mb of a loci previously published by Teslovich *et al*<sup>2</sup> or GLGC,<sup>3</sup> 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 1 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 ( $p \text{ value} < 2.63 \times 10^{-3}$ ). 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 discovery 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 of the five replicated variants, one attained genome-wide significance ( $p \text{ value} < 5 \times 10^{-8}$ ) and the other four nominal significance ( $p \text{ value} < 0.05$ ).

## 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



**Figure 1** Manhattan plots for HDL-C (A), LDL-C (B), TC (C) and TG (D) after the meta-analysis of all discovery cohorts. Variants that were present in at least four cohorts and that are not within 0.5 Mb of a previously published loci<sup>2,3</sup> were included. The black line indicates the genome-wide significant line ( $5 \times 10^{-8}$ ), the black and red dots the variants identified by GCTA which are not genome-wide significant and which are genome-wide significant, respectively. HDL-C, high-density lipoprotein cholesterol; LDL-C, low-density lipoprotein cholesterol; TC, total cholesterol; TG, triglycerides.

reference panel. The meta-analysis, followed by GCTA analysis revealed 19 associations with MAF ranging from 0.01 to 0.48. Of the 19 associations, we were able to replicate five in an independent sample of approximately 90 000 individuals.

One of the five associations we identified is between TG and rs116843064, an exonic variant in the *ANGPTL4* gene on chromosome 19 (figure 2C). This missense variant changes the amino acid glutamic acid into lysine (Glu40Lys) and is predicted to be damaging for the structure and function of the protein by Polyphen2,<sup>8</sup> MutationTaster<sup>9</sup> and likelihood ratio test (LRT).<sup>10</sup> *ANGPTL4* is significantly associated with the Kyoto Encyclopedia of Genes and Genomes (KEGG) term fatty acid metabolism, the GO process lipid storage and the gene ontology (GO) cellular component lipid particle (p value of  $1.10 \times 10^{-6}$ ,  $1.31 \times 10^{-10}$  and  $2.87 \times 10^{-18}$ , respectively, genenetwork.nl). *ANGPTL4* has been associated with HDL-C before using the GWAS approach<sup>2</sup> and with TG before using an exome sequencing approach<sup>11</sup> and more recently using the GWAS approach.<sup>1</sup> We therefore do not claim this finding as novel, though this is the smallest study in which this variant was genome-wide significantly associated with TG and replicated in an independent sample.

The second new finding we identified is the association between TC and rs6457374, an intergenic variant located on chromosome 6 between the genes *HLA-C* and *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 *HLA-C* and *HLA-B*, respectively, genenetwork.nl) which is in line with, among others, a previously published association between TC and an exonic variant in the *ABCA6* gene which is also an ABC transporter.<sup>12</sup> ABC transporters transport a wide variety of substrates across extracellular and intracellular membranes, including lipids.<sup>13</sup>

The third finding of this study is the association between HDL-C and rs77697917, an intergenic variant on chromosome

17 between the genes *SOST* and *DUSP3* (figure 2B). *DUSP3* is associated with the regulation and function of carbohydrate-responsive element-binding protein (ChREBP) in the liver (p value =  $3.03 \times 10^{-5}$ , genenetwork.nl). ChREBP mediates the activation of several regulatory enzymes involved in lipogenesis.<sup>14–18</sup> This variant is in high linkage disequilibrium ( $D' = 0.936$ ) in the 1 kG with rs72836561, an exonic variant in the gene *CD300LG* (MAF = 0.027,  $\beta = -2.437$ ,  $se_{\beta} = 0.381$ , 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,<sup>8</sup> MutationTaster<sup>9</sup> and LRT.<sup>10</sup> This amino acid polymorphism has been associated with HDL-C in exome-wide association studies<sup>19</sup> and TG in GWAS<sup>1</sup> 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 *LPA* (Lipoprotein, Lp(A)) gene and the *PLG* (Plasminogen) gene. The *LPA* gene has been associated before with LDL-C and TC before.<sup>2</sup> The reported lead SNP was rs1564348, which in the newer human genome versions is annotated to the *SLC22A1* (Solute Carrier Family 22 (Organic Cation Transporter), Member 1) gene instead of the *LPA* gene. This explains why we again identified a locus near the *LPA* gene, which has been identified by others as well.<sup>1</sup>

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.

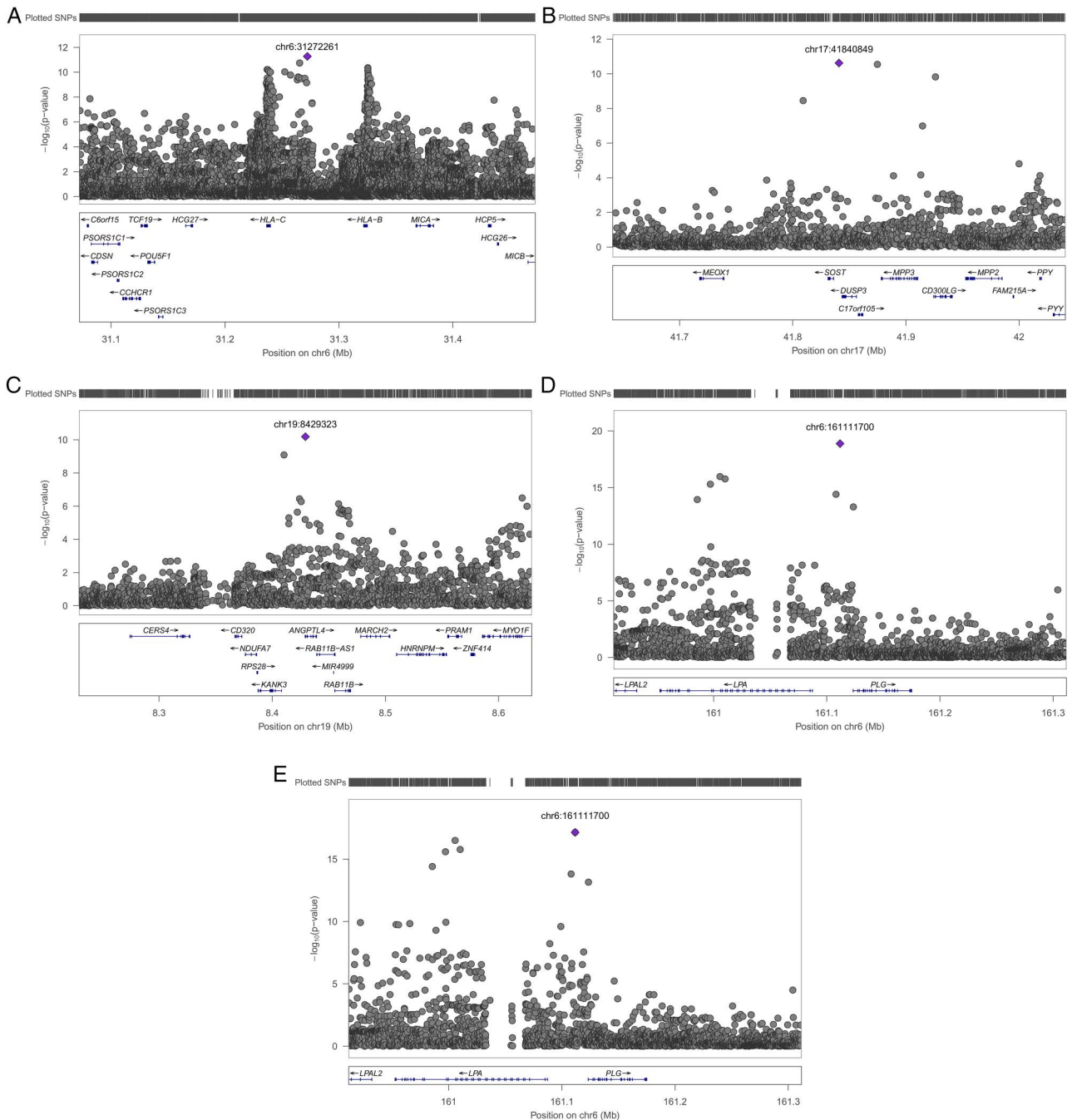
**Table 1** The results for the 19 variants after the meta-analysis of all discovery cohorts, all replication cohorts and all cohorts combined

Trait	Chr:Position	rs identifier	nearest gene	A1/A2	Discovery cohorts					Replication cohorts					All cohorts combined			
					Freq	N	$\beta$	SE $_{\beta}$	p Value	Freq	N	$\beta$	SE $_{\beta}$	p Value	Freq	$\beta$	SE $_{\beta}$	p Value
HDL-C	3:72 067 255	rs75909755	<i>PROL2-EIF4E3</i>	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	<b>rs6457374</b>	<i>HLA-B</i>	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	<i>HLA-B</i>	C/G	0.53	37 981	-2.201	0.344	1.62E-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	-	<i>CDKN1A</i>	CAG/C	0.45	53 425	-0.019	0.003	7.63E-09	0.49	59 018	-0.003	0.004	5.20E-01	0.46	-0.013	0.003	5.93E-07
TG	6:13 983 949 8	rs608736	-	C/G	0.48	53 425	-0.019	0.003	5.67E-09	0.49	73 512	-0.008	0.003	2.67E-02	0.48	-0.013	0.002	9.10E-09
TG	6:16 085 176 6	rs376563	<i>SLC22A3</i>	T/C	0.46	47 036	-0.02	0.003	3.37E-09	0.46	73 512	-0.001	0.003	8.22E-01	0.46	-0.010	0.002	1.36E-05
LDL-C	6:16 111 170 0	<b>rs186696265</b>	<i>LPA-PLG</i>	T/C	0.01	49 221	11.247	1.241	1.31E-19	0.01	59 497	0.263	0.076	5.42E-04	0.01	0.304	0.076	6.17E-05
TC	6:16 111 170 0	<b>rs186696265</b>	<i>LPA-PLG</i>	T/C	0.01	59 859	10.004	1.162	7.20E-18	0.01	75 821	0.238	0.075	1.46E-03	0.01	0.278	0.075	1.93E-04
HDL-C	7:80 492 357	rs60839105	<i>SEMA3C</i>	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	<i>CPA6</i>	A/G	0.11	17 361	6.552	1.147	1.12E-08	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	<i>PCSK5</i>	T/C	0.99	43 398	8.529	1.449	3.99E-09	0.99	51 367	0.068	0.103	5.11E-01	0.99	0.110	0.103	2.84E-01
TC	9:78 728 065	rs146369471	<i>PCSK5</i>	T/C	0.99	53 787	7.978	1.413	1.64E-08	0.99	70 241	0.015	0.103	8.84E-01	0.99	0.057	0.103	5.79E-01
TC	12:51 207 704	rs829112	<i>ATF1</i>	A/G	0.68	56 924	1.448	0.258	2.02E-08	0.73	87 659	0.009	0.012	4.63E-01	0.73	0.012	0.012	3.18E-01
TG	13:11 454 402 4	rs7140110	<i>GAS6</i>	T/C	0.71	48 221	-0.021	0.004	3.65E-08	0.72	60 437	-0.006	0.005	2.68E-01	0.72	-0.015	0.003	5.13E-07
TG	15:43 726 625	rs150844304	<i>TP53BP1</i>	A/C	0.97	52 720	-0.083	0.01	2.52E-17	0.95	63 884	-0.026	0.015	8.85E-02	0.96	-0.066	0.008	9.52E-16
TC	17:18 046 290	rs8065026	<i>MYO15A</i>	T/C	0.79	56 924	-1.644	0.292	1.76E-08	0.81	76 913	-0.026	0.013	4.93E-02	0.81	-0.029	0.013	2.66E-02
HDL-C	17:41 840 849	<b>rs77697917</b>	<i>SOST-DUSP3</i>	T/C	0.02	45 052	-2.717	0.407	2.38E-11	0.03	67 843	-0.222	0.036	4.27E-10	0.03	-0.241	0.035	1.04E-11
TG	19:8 429 323	<b>rs116843064</b>	<i>ANGPTL4</i>	A/G	0.03	35 643	-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	20:17 844 684	rs2618566	<i>BANF2-SNX5</i>	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,  $\beta$  is the effect of A1.

HDL-C, high-density lipoprotein cholesterol; LDL-C, low-density lipoprotein cholesterol; TC, total cholesterol; TG, triglycerides.



**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.

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 Project<sup>20</sup> 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 al*<sup>2</sup> and 43.4% of the findings of GLGC<sup>3</sup> despite our smaller sample. A high replication rate is expected based on the high overlap of our samples with the samples of Teslovich *et al*<sup>2</sup> and with the samples of GLGC<sup>3</sup> 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

exome sequencing of candidate genes. The p.Arg406X mutation in the *NPC1L1* gene (rs145297799), which was reported to be associated with reduced LDL-C levels and reduced risk of coronary heart disease,<sup>4</sup> is not available in the 1kG reference panel and, therefore, we were not able to replicate this finding. Do *et al*<sup>5</sup> 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,  $\beta = -0.093$ ,  $SE_{\beta} = 0.023$ ,  $p \text{ value} = 4.827 \times 10^{-5}$  and rs2075291,  $\beta = 0.219$ ,  $SE_{\beta} = 0.046$ ,  $p \text{ value} = 2.092 \times 10^{-6}$ ), but not significantly associated with LDL-C (rs34282181,  $\beta = -3.939$ ,  $SE_{\beta} = 1.861$ ,  $p \text{ value} = 0.034$  and rs2075291,  $\beta = -2.316$ ,  $SE_{\beta} = 3.001$ ,  $p \text{ value} = 0.440$ ). 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,  $\beta = -18.430$ ,  $SE_{\beta} = 7.140$ ,  $p \text{ value} = 9.848 \times 10^{-3}$ ). The third published finding we tried to replicate, was the association between *APOC3* and TG levels.<sup>6</sup> Of the seven variants reported, only one existed in our discovery meta-analysis (chromosome 11, position 116 701 354), which is associated with TG ( $\beta = -0.343$ ,  $SE_{\beta} = 0.113$ ,  $p \text{ value} = 2.311 \times 10^{-3}$ ). Those authors also reported an association between an *APOA5* variant (rs3135506) and TG as the most significant finding. This variant was also significantly associated with TG in our discovery meta-analysis ( $\beta = 0.129$ ,  $SE_{\beta} = 0.007$ ,  $p \text{ value} = 1.099 \times 10^{-87}$ ). 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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## REFERENCES

1 Surakka I, Horikoshi M, Mägi R, Sarin AP, Mahajan A, Lagou V, Marullo L, Ferreira T, Miraglio B, Timonen S, Kettunen J, Pirinen M, Karjalainen J, Thorleifsson G, Hägg S, Hottenga JJ, Isaacs A, Ladenvall C, Beekman M, Esko T, Ried JS, Nelson CP, Willenborg C, Gustafsson S, Westra HJ, Blades M, de Craen AJ, de Geus EJ, Deelen J, Grallert H, Hamsten A, Havulinna AS, Hengstenberg C, Houwing-Duistermaat JJ, Hyppönen E, Karssen LC, Lehtimäki T, Lyssenko V, Magnusson PK, Mihailov E, Müller-Nurasyid M, Mpondi JP, Pedersen NL, Penninx

BW, Perola M, Pers TH, Peters A, Rung J, Smit JH, Steinthorsdottir V, Tobin MD, Tsernikova N, van Leeuwen EM, Viikari JS, Willems SM, Willemssen G, Schunkert H, Erdmann J, Samani NJ, Kaprio J, Lind L, Gieger C, Metspalu A, Slagboom PE, Groop L, van Duijn CM, Eriksson JG, Jula A, Salomaa V, Boomsma DI, Power C, Raitakari OT, Ingelsson E, Järvelin MR, Thorsteinsdottir U, Franke L, Ikonen E, Kallioniemi O, Pietiäinen V, Lindgren CM, Stefansson K, Palotie A, McCarthy MI, Morris AP, Prokopenko I, Ripatti S, ENGAGE Consortium. The impact of low-frequency and rare variants on lipid levels. *Nat Genet* 2015;47:589–97.

2 Teslovich TM, Musunuru K, Smith AV, Edmondson AC, Stylianou IM, Koseki M, Pirruccello JP, Ripatti S, Chasman DI, Willer CJ, Johansen CT, Fouchier SW, Isaacs A, Peloso GM, Barbalic M, Ricketts SL, Bis JC, Aulchenko YS, Thorleifsson G, Feitosa MF, Chambers J, Orho-Melander M, Melander O, Johnson T, Li X, Guo X, Li M, Shin Cho Y, Jin Go M, Jin Kim Y, Lee JY, Park T, Kim K, Sim X, Tsee-Hee Ong R, Croteau-Chonka DC, Lange LA, Smith JD, Song K, Hua Zhao J, Yuan X, Luan J, Lamina C, Ziegler A, Zhang W, Zee RY, Wright AF, Witteman JC, Wilson JF, Willemssen G, Wichmann HE, Whitfield JB, Waterworth DM, Wareham NJ, Waeber G, Vollenweider P, Voight BF, Vitart V, Uitterlinden AG, Uda M, Tuomilehto J, Thompson JR, Tanaka T, Surakka I, Stringham HM, Spector TD, Soranzo N, Smit JH, Sinisalo J, Silander K, Silander JG, Scuteri A, Scott J, Schlessinger D, Sanna S, Salomaa V, Saharinen J, Sabatti C, Ruukonen A, Rudan I, Rose LM, Roberts R, Rieder M, Psaty BM, Pramstaller PP, Pichler I, Perola M, Penninx BW, Pedersen NL, Pattaro C, Parker AN, Pare G, Oostra BA, O'Donnell CJ, Nieminen MS, Nickerson DA, Montgomery GW, Meitinger T, McPherson R, McCarthy MI, McArdle W, Masson D, Martin NG, Marroni F, Mangino M, Magnusson PK, Lucas G, Luben R, Loos RJ, Lokki ML, Lettre G, Langenberg C, Launer LJ, Lakatta EG, Laaksonen R, Kyvik KO, Kronenberg F, König IR, Khaw KT, Kaprio J, Kaplan LM, Johansson A, Jarvelin MR, Janssens AC, Ingelsson E, Igl W, Kees Hovingh G, Hottenga JJ, Hofman A, Hicks AA, Hengstenberg C, Heid IM, Hayward C, Havulinna AS, Hastie ND, Harris TB, Haritunians T, Hall AS, Gyllenstein U, Guiducci C, Groop LC, Gonzalez E, Gieger C, Freimer NB, Ferraroli L, Erdmann J, Elliott P, Ejebe KG, Döring A, Dominiczak AF, Demissie S, Deloukas P, de Geus EJ, de Faire U, Crawford G, Collins FS, Chen YD, Caulfield MJ, Campbell H, Burt NP, Bonnycastle LL, Boomsma DI, Boekholdt SM, Bergman RN, Barroso I, Bandinelli S, Ballantyne CM, Assimes TL, Quertermous T, Altschuler D, Seielstad M, Wong TY, Tai ES, Feranil AB, Kuzawa CW, Adair LS, Taylor HA Jr, Borecki IB, Gabriel SB, Wilson JG, Holm H, Thorsteinsdottir U, Gudnason V, Krauss RM, Mohlke KL, Ordovas JM, Munroe PB, Kooner JS, Tall AR, Hegele RA, Kastelein JJ, Schadt EE, Rotter JJ, Boerwinkle E, Strachan DP, Mooser V, Stefansson K, Reilly MP, Samani NJ, Schunkert H, Cupples LA, Sandhu MS, Ridker PM, Rader DJ, van Duijn CM, Peltonen L, Abecasis GR, Boehnke M, Kathiresan S. Biological, clinical and population relevance of 95 loci for blood lipids. *Nature* 2010;466:707–13.

3 Global Lipids Genetics Consortium Willer CJ, Schmidt EM, Sengupta S, Peloso GM, Gustafsson S, Kanoni S, Ganna A, Chen J, Buchkovich ML, Mora S, Beckmann JS, Bragg-Gresham JL, Chang HY, Demirkan A, Den Hertog HM, Do R, Donnelly LA, Ehret GB, Esko T, Feitosa MF, Ferreira T, Fischer K, Fontanillas P, Fraser RM, Freitag DF, Gurdasani D, Heikkilä K, Hyppönen E, Isaacs A, Jackson AU, Johansson A, Johnson T, Kaakinen M, Kettunen J, Kleber ME, Li X, Luan J, Lytikäinen LP, Magnusson PK, Mangino M, Mihailov E, Montasser ME, Müller-Nurasyid M, Nolte IM, O'Connell JR, Palmer CD, Perola M, Petersen AK, Sanna S, Saxena R, Service SK, Shah S, Shungin D, Sidore C, Song C, Strawnbridge RJ, Surakka I, Tanaka T, Teslovich TM, Thorleifsson G, Van den Herik EG, Voight BF, Volcik KA, Waite LL, Wong A, Wu Y, Zhang W, Absher D, Asiki G, Barroso I, Been LF, Bolton JL, Bonnycastle LL, Brambilla P, Burnett MS, Cesana G, Dimitriou M, Doney AS, Döring A, Elliott P, Epstein SE, Eyjolfsson GI, Gigante B, Goodarzi MO, Grallert H, Gravitto ML, Groves CJ, Hallmans G, Hartikainen AL, Hayward C, Hernandez D, Hicks AA, Holm H, Hung YJ, Illig T, Jones MR, Kaleebu P, Kastelein JJ, Khaw KT, Kim E, Klopp N, Komulainen P, Kumari M, Langenberg C, Lehtimäki T, Lin SY, Lindström J, Loos RJ, Mach F, McArdle WL, Meisinger C, Mitchell BD, Müller G, Nagaraja R, Narisu N, Nieminen TV, Nsubuga RN, Olafsson I, Ong KK, Palotie A, Papamarkou T, Pomilla C, Pouta A, Rader DJ, Reilly MP, Ridker PM, Rivadeneira F, Rudan I, Ruukonen A, Samani N, Scharnagl H, Sealey J, Silander K, Stancáková A, Stirrups K, Swift AJ, Tietel U, Uitterlinden AG, van Pelt LJ, Vedantam S, Wainwright N, Wijmenga C, Wild SH, Willemssen G, Wilsgaard T, Wilson JF, Young EH, Zhao JH, Adair LS, Arveiler D, Assimes TL, Bandinelli S, Bennett F, Bochud M, Boehm BO, Boomsma DI, Borecki IB, Bornstein SR, Bovet P, Burnier M, Campbell H, Chakravarti A, Chambers JC, Chen YD, Collins FS, Cooper RS, Danesh J, Dedoussis G, de Faire U, Feranil AB, Ferrières J, Ferrucci L, Freimer NB, Gieger C, Groop LC, Gudnason V, Gyllenstein U, Hamsten A, Harris TB, Hingorani A, Hirschhorn JN, Hofman A, Hovingh GK, Hsiung CA, Humphries SE, Hunt SC, Hveem K, Iribarren C, Järvelin MR, Jula A, Kähönen M, Kaprio J, Kesäniemi A, Kivimäki M, Kooner JS, Koudstaal PJ, Krauss RM, Kuh D, Kuusisto J, Kyvik KO, Laakso M, Lakka TA, Lind L, Lindgren CM, Martin NG, März W, McCarthy MI, McKenzie CA, Meneton P, Metspalu A, Moilanen L, Morris AD, Munroe PB, Njolstad I, Pedersen NL, Power C, Pramstaller PP, Price JF, Psaty BM, Quertermous T, Rauramaa R, Saleheen D, Salomaa V, Sanghera DK, Saramies J, Schwarz PE, Sheu WH, Shuldiner AR, Siegbahn A, Spector TD, Stefansson K, Strachan DP, Tayo BO, Tremoli E, Tuomilehto J, Uusitupa M, van Duijn CM, Vollenweider P, Wallentin L, Wareham NJ, Whitfield JB, Wolfenbuttel BH, Ordovas



- JM, Boerwinkle E, Palmer CN, Thorsteinsdottir U, Chasman DI, Rotter JJ, Franks PW, Ripatti S, Cupples LA, Sandhu MS, Rich SS, Boehnke M, Deloukas P, Kathiresan S, Mohlke KL, Ingelsson E, Abecasis GR. Discovery and refinement of loci associated with lipid levels. *Nat Genet* 2013;45:1274–83.
- 4 Myocardial Infarction Genetics Consortium Investigators. Stitzel NO, Won HH, Morrison AC, Peloso GM, Do R, Lange LA, Fontanillas P, Gupta N, Duga S, Goel A, Farrall M, Saleheen D, Ferrario P, König I, Asselta R, Merlini PA, Marziliano N, Notarangelo MF, Schick U, Auer P, Assimes TL, Reilly M, Wilensky R, Rader DJ, Hovingh GK, Meitinger T, Kessler T, Kastrati A, Laugwitz KL, Siscovick D, Rotter JJ, Hazen SL, Tracy R, Cresci S, Spertus J, Jackson R, Schwartz SM, Natarajan P, Crosby J, Muzny D, Ballantyne C, Rich SS, O'Donnell CJ, Abecasis G, Sunyaev S, Nickerson DA, Buring JE, Ridker PM, Chasman DI, Austin E, Ye Z, Kullo IJ, Weeke PE, Shaffer CM, Bastarache LA, Denny JC, Roden DM, Palmer C, Deloukas P, Lin DY, Tang ZZ, Erdmann J, Schunkert H, Danesh J, Marrugat J, Elosua R, Ardissino D, McPherson R, Watkins H, Reiner AP, Wilson JG, Altschuler D, Gibbs RA, Lander ES, Boerwinkle E, Gabriel S, Kathiresan S. Inactivating mutations in NPC1L1 and protection from coronary heart disease. *N Engl J Med* 2014;371:2072–82.
- 5 Do R, Stitzel NO, Won HH, Jørgensen AB, Duga S, Angelica Merlino P, Kiezun A, Farrall M, Goel A, Zuk O, Guella I, Asselta R, Lange LA, Peloso GM, Auer PL; NHLBI Exome Sequencing Project. Giarelli D, Martinelli N, Farlow DN, DePristo MA, Roberts R, Stewart AF, Saleheen D, Danesh J, Epstein SE, Sivapalaratnam S, Hovingh GK, Kastelein JJ, Samani NJ, Schunkert H, Erdmann J, Shah SH, Kraus WE, Davies R, Nikpay M, Johansen CT, Wang J, Hegele RA, Hechter E, Marz W, Kleber ME, Huang J, Johnson AD, Li M, Burke GL, Gross M, Liu Y, Assimes TL, Heiss G, Lange EM, Folsom AR, Taylor HA, Olivieri O, Hamsten A, Clarke R, Reilly DF, Yin W, Rivas MA, Donnelly P, Rossouw JE, Psaty BM, Herrington DM, Wilson JG, Rich SS, Bamshad MJ, Tracy RP, Cupples LA, Rader DJ, Reilly MP, Spertus JA, Cresci S, Hartiala J, Tang WH, Hazen SL, Allayee H, Reiner AP, Carlson CS, Kooperberg C, Jackson RD, Boerwinkle E, Lander ES, Schwartz SM, Siscovick DS, McPherson R, Tybjaerg-Hansen A, Abecasis GR, Watkins H, Nickerson DA, Ardissino D, Sunyaev SR, O'Donnell CJ, Altschuler D, Gabriel S, Kathiresan S. Exome sequencing identifies rare LDLR and APOA5 alleles conferring risk for myocardial infarction. *Nature* 2015;518:102–6.
- 6 The TG and HDL Working Group of the Exome Sequencing Project, National Heart, Lung, and Blood Institute; Crosby J, Peloso GM, Auer PL, Crosslin DR, Stitzel NO, Lange LA, Lu Y, Tang ZZ, Zhang H, Hindy G, Masca N, Stirrups K, Kanoni S, Do R, Jun G, Hu Y, Kang HM, Xue C, Goel A, Farrall M, Duga S, Merlini PA, Asselta R, Giarelli D, Olivieri O, Martinelli N, Yin W, Reilly D, Speliotes E, Fox CS, Hveem K, Holmen OL, Nikpay M, Farlow DN, Assimes TL, Franceschini N, Robinson J, North KE, Martin LW, DePristo M, Gupta N, Escher SA, Jansson JH, Van Zuydam N, Palmer CN, Wareham N, Koch W, Meitinger T, Peters A, Lieb W, Erbel R, Konig IR, Kruppa J, DeGenhardt F, Gottesman O, Bottinger EP, O'Donnell CJ, Psaty BM, Ballantyne CM, Abecasis G, Ordovas JM, Melander O, Watkins H, Orho-Melander M, Ardissino D, Loos RJ, McPherson R, Willer CJ, Erdmann J, Hall AS, Samani NJ, Deloukas P, Schunkert H, Wilson JG, Kooperberg C, Rich SS, Tracy RP, Lin DY, Altschuler D, Gabriel S, Nickerson DA, Jarvik GP, Cupples LA, Reiner AP, Boerwinkle E, Kathiresan S. Loss-of-function mutations in APOC3, triglycerides, and coronary disease. *N Engl J Med* 2014;371:22–31.
- 7 Yang J, Lee SH, Goddard ME, Visscher PM. GCTA: a tool for genome-wide complex trait analysis. *Am J Hum Genet* 2011;88:76–82.
- 8 Adzhubei IA, Schmidt S, Peshkin L, Ramensky VE, Gerasimova A, Bork P, Kondrashov AS, Sunyaev SR. A method and server for predicting damaging missense mutations. *Nat Methods* 2010;7:248–9.
- 9 Schwarz JM, Rödelsperger C, Schuelke M, Seelow D. MutationTaster evaluates disease-causing potential of sequence alterations. *Nat Methods* 2010;7:575–6.
- 10 Chun S, Fay JC. Identification of deleterious mutations within three human genomes. *Genome Res* 2009;19:1553–61.
- 11 Romeo S, Pennacchio LA, Fu Y, Boerwinkle E, Tybjaerg-Hansen A, Hobbs HH, Cohen JC. Population-based resequencing of ANGPTL4 uncovers variations that reduce triglycerides and increase HDL. *Nat Genet* 2007;39:513–16.
- 12 van Leeuwen EM, Karssen LC, Deelen J, Isaacs A, Medina-Gomez C, Mbarek H, Kanterakis A, Trompet S, Postmus I, Verweij N, van Enckevort DJ, Huffman JE, White CC, Feitosa MF, Bartz TM, Manichaikul A, Joshi PK, Peloso GM, Deelen P, van Dijk F, Willemsen G, de Geus EJ, Milaneschi Y, Penninx BW, Francioli LC, Menelaou A, Pulit SL, Rivadeneira F, Hofman A, Oostra BA, Franco OH, Mateo Leach I, Beekman M, de Craen AJ, Uh HW, Trochet H, Hocking LJ, Porteous DJ, Sattar N, Packard CJ, Buckley BM, Brody JA, Bis JC, Rotter JJ, Mychalekij JC, Campbell H, Duan Q, Lange LA, Wilson JF, Hayward C, Polasek O, Vitart V, Rudan I, Wright AF, Rich SS, Psaty BM, Borecki IB, Kearney PM, Stott DJ, Adrienne Cupples L; Genome of The Netherlands Consortium, Jukema JW, van der Harst P, Sijbrands EJ, Hottenga JJ, Uitterlinden AG, Swertz MA, van Ommen GJ, de Bakker PI, Eline Slagboom P, Boomsma DI, Wijmenga C, van Duijn GM. The genome of the Netherlands population-specific imputations identify an ABCA6 variant associated with cholesterol levels. *Nat Commun* 2015;6:6065.
- 13 Jones PM, George AM. The ABC transporter structure and mechanism: perspectives on recent research. *Cell Mol Life Sci* 2004;61:682–99.
- 14 Towle HC. Glucose as a regulator of eukaryotic gene transcription. *Trends Endocrinol Metab* 2005;16:489–94.
- 15 Dentin R, Pégurier JP, Benhamed F, Fougelle F, Ferré P, Fauveau V, Magnuson MA, Girard J, Postic C. Hepatic glucokinase is required for the synergistic action of ChREBP and SREBP-1c on glycolytic and lipogenic gene expression. *J Biol Chem* 2004;279:20314–26.
- 16 Dentin R, Girard J, Postic C. Carbohydrate responsive element binding protein (ChREBP) and sterol regulatory element binding protein-1c (SREBP-1c): two key regulators of glucose metabolism and lipid synthesis in liver. *Biochimie* 2005;87:81–6.
- 17 Ma L, Robinson LN, Towle HC. ChREBP\* Mlx is the principal mediator of glucose-induced gene expression in the liver. *J Biol Chem* 2006;281:28721–30.
- 18 Uyeda K, Repa JJ. Carbohydrate response element binding protein, ChREBP, a transcription factor coupling hepatic glucose utilization and lipid synthesis. *Cell Metab* 2006;4:107–10.
- 19 Albrechtsen A, Grarup N, Li Y, Sparsø T, Tian G, Cao H, Jiang T, Kim SY, Korneliusen T, Li Q, Nie C, Wu R, Skotte L, Morris AP, Ladenvall C, Cauchi S, Stančáková A, Andersen G, Astrup A, Banasik K, Bennett AJ, Bolund L, Charpentier G, Chen Y, Dekker JM, Doney AS, Dorkhan M, Forsen T, Frayling TM, Groves CJ, Gui Y, Hallmans G, Hattersley AT, He K, Hitman GA, Holmkvist J, Huang S, Jiang H, Jin X, Justesen JM, Kristiansen K, Kuusisto J, Lajer M, Lantieri O, Li W, Liang H, Liao Q, Liu X, Ma T, Ma X, Manijak MP, Marre M, Mokrosiński J, Morris AD, Mu B, Nielsen AA, Nijpels G, Nilsson P, Palmer CN, Rayner NW, Renström F, Ribel-Madsen R, Robertson N, Rolandsson O, Rossing P, Schwartz TW; D.E.S.I.R. Study Group, Slagboom PE, Sterner M; DIAGRAM Consortium, Tang M, Tarnow L, Tuomi T, van't Riet E, van Leeuwen N, Varga TV, Vestmar MA, Walker M, Wang B, Wang Y, Wu H, Xi F, Yengo L, Yu C, Zhang X, Zhang J, Zhang Q, Zhang W, Zheng H, Zhou Y, Altschuler D, 't Hart LM, Franks PW, Balkau B, Froguel P, McCarthy MI, Laakso M, Groop L, Christensen C, Brandslund I, Lauritzen T, Witte DR, Linneberg A, Jørgensen T, Hansen T, Wang J, Nielsen R, Pedersen O. Exome sequencing-driven discovery of coding polymorphisms associated with common metabolic phenotypes. *Diabetologia* 2013;56:298–310.
- 20 Gurdasani D, Carstensen T, Tekola-Ayele F, Pagan L, Tachmazidou I, Hatzikotoulas K, Karthikeyan S, Iles L, Pollard MO, Choudhury A, Ritchie GR, Xue Y, Asimit J, Nsubuga RN, Young EH, Pomilla C, Kivinen K, Rockett K, Kamali A, Doumatey AP, Asiki G, Seeley J, Sisay-Joof F, Jallow M, Tollman S, Mekonnen E, Ekong R, Oljira T, Bradman N, Bojang K, Ramsay M, Adeyemo A, Bekele E, Motala A, Norris SA, Pirie F, Kaleebu P, Kwiatkowski D, Tyler-Smith C, Rotimi C, Zeggini E, Sandhu MS. The African Genome Variation Project shapes medical genetics in Africa. *Nature* 2015;517:327–32.