

Genetic invalidation of Lp-PLA₂ as a therapeutic target: Large-scale study of five functional Lp-PLA₂-lowering alleles

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Abstract

Aims: Darapladib, a potent inhibitor of lipoprotein-associated phospholipase A₂ (Lp-PLA₂), has not reduced risk of cardiovascular disease outcomes in recent randomized trials. We aimed to test whether Lp-PLA₂ enzyme activity is causally relevant to coronary heart disease.

Methods: In 72,657 patients with coronary heart disease and 110,218 controls in 23 epidemiological studies, we genotyped five functional variants: four rare loss-of-function mutations (c.109+2T > C (rs142974898), Arg82His (rs144983904), Val279Phe (rs76863441), Gln287Ter (rs140020965)) and one common modest-impact variant (Val379Ala (rs1051931)) in PLA2G7, the gene encoding Lp-PLA₂. We supplemented de-novo genotyping with information on a further 45,823 coronary heart disease patients and 88,680 controls in publicly available databases and other previous studies. We conducted a systematic review of randomized trials to compare effects of darapladib treatment on soluble Lp-PLA₂ activity, conventional cardiovascular risk factors, and coronary heart disease risk with corresponding effects of Lp-PLA₂-lowering alleles.

Results: Lp-PLA₂ activity was decreased by 64% ($p = 2.4 \times 10^{-25}$) with carriage of any of the four loss-of-function variants, by 45% ($p < 10^{-300}$) for every allele inherited at Val279Phe, and by 2.7% ($p = 1.9 \times 10^{-12}$) for every allele inherited at Val379Ala. Darapladib 160 mg once-daily reduced Lp-PLA₂ activity by 65% ($p < 10^{-300}$). Causal risk ratios for coronary heart disease per 65% lower Lp-PLA₂ activity were: 0.95 (0.88–1.03) with Val279Phe; 0.92 (0.74–1.16) with carriage of any loss-of-function variant; 1.01 (0.68–1.51) with Val379Ala; and 0.95 (0.89–1.02) with darapladib treatment.

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Conclusions: In a large-scale human genetic study, none of a series of Lp-PLA₂-lowering alleles was related to coronary heart disease risk, suggesting that Lp-PLA₂ is unlikely to be a causal risk factor.

Keywords

Human genetics, target validation, coronary heart disease, lipoprotein-associated phospholipase A₂, darapladib

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Introduction

Lipoprotein-associated phospholipase A₂ (Lp-PLA₂), an enzyme expressed by inflammatory cells in atherosclerotic plaques, is carried in the circulation bound predominantly to low-density lipoprotein (LDL).^{1,2} Lp-PLA₂ (also called platelet-activating factor acetyl hydrolase) hydrolyses oxidized phospholipids to yield pro-inflammatory products implicated in endothelial dysfunction, plaque inflammation and formation of necrotic core in plaque.¹ Observational³ and experimental studies in humans and animals have suggested that Lp-PLA₂ could be a valid therapeutic target, postulating this enzyme to link oxidative modification of LDL and development of inflammatory responses to arterial intima.¹ Previous studies have investigated genetic variants altering Lp-PLA₂ function in relation to coronary heart disease (CHD) risk.^{4,5} However, these studies have generally yielded inconclusive, or conflicting results,^{4,5} perhaps due to limited statistical power and due to limited knowledge about variants altering Lp-PLA₂ function (e.g. previous studies have been able to consider only one loss-of-function variant in *PLA2G7*, the gene encoding Lp-PLA₂).

However, two phase 3 randomized trials of darapladib, a potent inhibitor of Lp-PLA₂ activity, have not shown reductions in cardiovascular risk.^{6,7} These results could, at least in part, have been due to features of the trials. One of the phase 3 trials was restricted to patients recently hospitalized with acute coronary syndromes,⁶ yet many cardiovascular events occurring early after acute coronary syndromes may relate to thrombotic mechanisms and not be modifiable through Lp-PLA₂ inhibition. Trials used statins as background therapy, so any Lp-PLA₂ inhibition achieved with statins could have reduced any incremental benefits of darapladib. Trials could not assess the effects of prolonged Lp-PLA₂ inhibition because they recorded only about 3–4 years of median follow-up.^{6,7}

An alternative explanation is that darapladib did not reduce cardiovascular risk because Lp-PLA₂ is not a causal risk factor in cardiovascular disease. We tested this possibility by investigating natural loss of Lp-PLA₂ activity. Studies of Lp-PLA₂-lowering alleles should complement randomized trials of darapladib because genotypes are fixed at conception, avoiding potential

distorting effects of pre-existing disease and medication usage. Furthermore, Lp-PLA₂-lowering alleles should produce lifelong, rather than shorter-term, Lp-PLA₂ inhibition.

In over 260,000 participants of European, South Asian, or East Asian ancestries, we studied five functional variants in *PLA2G7*. We compared effects of Lp-PLA₂-lowering alleles on soluble Lp-PLA₂ activity, conventional cardiovascular risk factors and CHD risk with corresponding effects of darapladib, using results from randomized trials.

Methods

Study design

Figure 1 summarizes the study approach. Table 1 provides definitions and sources of data used. First, we identified four loss-of-function mutations and one missense variant in *PLA2G7* suggested by previous experimental and bioinformatics studies, thereby developing an allelic series for Lp-PLA₂ activity. Second, we assessed associations of these variants – both singly and in combination – with soluble Lp-PLA₂ activity, conventional cardiovascular risk factors and CHD risk in people of European, South Asian or East Asian ancestries. Third, we compared associations of Lp-PLA₂-lowering alleles with the aforementioned traits and CHD risk with the effects of darapladib treatment through a systematic review of randomized trials.

Genetic variants

We defined loss-of-function variants as non-synonymous variants with in vitro or in vivo evidence demonstrating complete lack of Lp-PLA₂ activity or sequence changes expected to abolish Lp-PLA₂ function (e.g. nonsense variants or mutations in essential splice sites). We selected variants through a systematic search for loss-of-function variants using the UniProt database,⁸ the Exome Aggregation Consortium database (Cambridge, MA, USA; URL: <http://exac.broadinstitute.org> (accessed November 2014)),⁹ studies of site-directed mutagenesis^{10–12} and results from targeted gene sequencing.¹³ Among the full set of variants identified (Supplementary Material online Table 1),

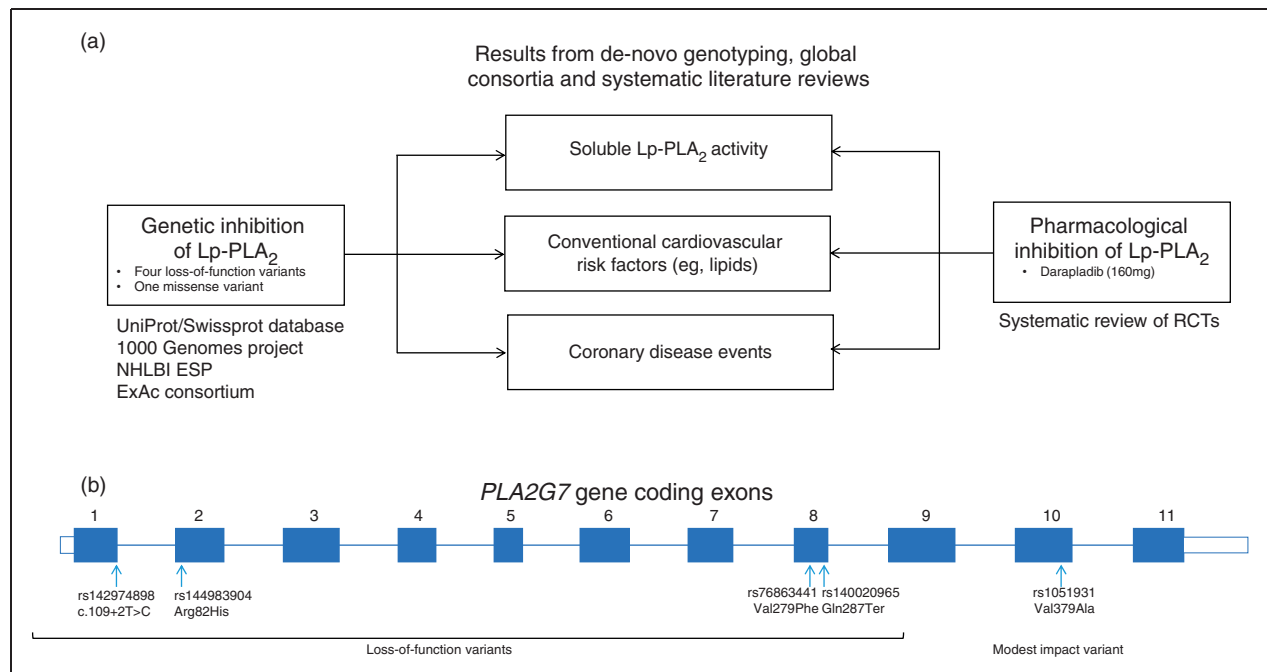


Figure 1. Summary of study design. (a) Flow chart of study design. (b) Exonic structure of the *PLA2G7* gene and location of variants used in this study.

ExAc: Exome Aggregation consortium; NHLBI ESP: National Heart Lung and Blood Institute Exome Sequencing Project; Lp-PLA₂: lipoprotein-associated phospholipase A₂; RCT: randomized controlled trial; UniProt/Swissprot: manually annotated and reviewed section of the Universal Protein resource database.

we selected the following variants that could be detected in the 1000 Genomes¹⁴ or the NHLBI Exome Sequencing Project¹⁵ projects (and, hence, potentially studied at the population level): the splice site mutation 109+2T>C (rs142974898); two non-synonymous variants – Arg82His (rs144983904) and Val279Phe (rs76863441); and the nonsense variant Gln287Ter (rs140020965). These loss-of-function variants are rare in European and South Asian ancestry populations, whereas carriage of 279Phe is common in East Asian ancestry populations and abolition of Lp-PLA₂ activity is well documented.¹⁶ Additionally, we studied Val379Ala (rs1051931), a functional variant common in European ancestry populations, which lowers Lp-PLA₂ activity only modestly,^{10,17} in contrast with the much stronger Lp-PLA₂-lowering achieved by the loss-of-function variants described above.

Samples and data for genetic studies

We aimed to maximize study power and comprehensiveness by using the following complementary approaches to generate new data on, as well as to collate systematically existing relevant information about, the *PLA2G7* variants mentioned above: (1) we conducted de-novo genotyping for 72,657 CHD patients and 110,218 controls (the majority of whom also had

information available on some cardiovascular risk factors); (2) we accessed non-overlapping summary-level data from the only known global genetics consortium of CHD,¹⁸ yielding information on a further 35,735 CHD patients and 73,481 controls; (3) we conducted a systematic review (supplemented by provision of tabular data from each study investigator) of published East Asian CHD studies of Val279Phe because these studies were not represented in the global CHD consortium, yielding information on a further 10,088 CHD cases and 15,199 controls; (4) we accessed summary-level data from the largest available global genetics consortium on each of several relevant cardiovascular risk factors (e.g. Lp-PLA₂ activity, conventional lipids, blood pressure), yielding information on 489,045 participants. Each of these sources of information is summarized below and in Table 1, with a key in Table 1's legend denoting the level of data detail available for each source (e.g. individual-participant data versus tabular study-level results).

Coronary heart disease outcomes. For CHD outcomes, we had access to data for a total of 92,995 patients and 162,228 controls. For 182,875 of these participants (72,657 CHD patients, 110,218 controls), we did de-novo genotyping of the four loss-of-function variants (c.109+2T>C, Arg82His, Val279Phe, Gln287Ter)

Table 1. Definitions and source of contributing data for the main study outcome.

	Val279Phe, loss-of-function variant common in East Asians	Four loss-of-function variants^a, rare in Europeans and South Asians	Val379Ala, modest impact variant	Darapladib
Data sources	Systematic review: up to 12 East Asian studies	De-novo genotyping and participant-level data: up to eight European or South Asian ancestry studies from the CHD Exome ⁺ consortium ^{19,26} De-novo genotyping and study-level data: up to 15 European ancestry studies from the MICAD Exome consortium ³⁸ and three European ancestry studies from the CHARGE Consortium ^{17,29} Plus publicly available consortium data	up to eight European or South Asian ancestry studies from the CHD Exome ⁺ consortium ³⁸ and three European ancestry studies from the MICAD Exome consortium ³⁸ and three European ancestry studies from the CHARGE Consortium ^{17,29} Plus publicly available consortium data	Systematic review: up to five randomized clinical trials ^{6,7,39-41} from a systematic review
Lp-PLA₂ assessment tool				
Endpoint	Number of studies and unique individuals contributing to analyses; n total or cases/controls			
Coronary heart disease^b	Seven East Asian studies ^c	Eight European or South Asian ancestry studies from the CHD Exome ⁺ consortium ^{19,26 d}	Eight European or South Asian ancestry studies from the MICAD Exome consortium ^{38 c}	Four European or South Asian ancestry studies from the C4D consortium ^{27 e}
	10,088 cases 15,199 controls	35,829 cases 44,948 controls	14,976 cases 32,084 controls	15,420 cases 15,062 controls
Lp-PLA₂ activity^f	12 East Asian studies ^c	One European ancestry study from the CHD Exome ⁺ consortium ^{25 d}	Two European ancestry studies from the CHD Exome ⁺ consortium ^{22,23,25 d}	Three European ancestry studies from the CHARGE consortium ^{17 c}
	8468	1240	2173	854
		8564	11,662	

(continued)

Table 1. Continued.

Endpoint	Val1279Phe, loss-of-function variant common in East Asians		Four loss-of-function variants ^a , rare in Europeans and South Asians		Val1379Ala, modest impact variant		Dara-pladib			
	Conventional risk factors ^f	12 East Asian studies ^c	17,898	76,584	Eight European or South Asian ancestry studies from the CHD Exome ⁺ consortium ^{19,26 d}	71,256		Eight European or South Asian ancestry studies from the CHD Exome ⁺ consortium ^{19,26 d}	51,201	Publicly available consortium data ^e
BMI		17,898	76,584	71,256	51,201	126,142 from 46 studies from the GIANT consortium ⁴²	NA			
Blood pressure		6705	72,450	71,256	71,256	69,245 from 29 studies from the ICBP consortium ⁴³	323			
Lipids		17,643	76,826	55,431	55,431	94,311 from 46 studies from the GLGC consortium ⁴⁴	803			
C-reactive protein		2914	40,484	41,442	41,442	66,185 from 15 studies from the CHARGE consortium ⁴⁵	848			
Glycaemic traits		2914	9420	9408	9408	46,186 from 21 studies from the MAGIC consortium ⁴⁶	NA			
eGFR		4017	32,929	32,190	32,190	74,354 from 26 studies from the CKDGen consortium ⁴⁷	NA			

Further detail on the individual studies is provided in Supplementary Tables 2 and 3 online.

^ars142974898 (c.109+2T>C), rs144983904 (Arg82His), rs76863441 (Val1279Phe), rs140020965 (Gln287Ter); see also Figure 1(b) for further variant details.

^bIn genetic analysis, CHD was defined as myocardial infarction and other major coronary events (~90% of cases) or angiographic stenosis only (~10% of cases); see Supplementary Tables 2 and 3 for details.

^cSummary/tabular analysis CHD was defined as fatal coronary disease, non-fatal myocardial infarction or urgent revascularization for myocardial ischaemia.

^dParticipant-level data available (by study).

^eMeta-analysis data available.

^fSee Supplementary Tables 2 and 3 for details on risk factor measurements.

BMI: body-mass index; C4D: Coronary Artery Disease Genetics consortium; CARDIoGRAM: Coronary ARtery Disease Genome wide Replication and Meta-analysis; CHARGE: Cohorts for Heart and Aging Research in Genomic Epidemiology; CHD: coronary heart disease; CKDGen: Chronic Kidney Disease Genetics consortium; eGFR: estimated glomerular filtration rate; GIANT: Genetic Investigation of Anthropometric Traits consortium; GLGC: Global Lipids Genetics Consortium; ICBP: International Consortium for Blood Pressure; Lp-PLA₂: lipoprotein associated phospholipase A₂; MAGIC: Meta-Analyses of Glucose and Insulin-related traits Consortium; NA: data not available

and Val379Ala using customized Exome arrays (Illumina, CA, USA) by technicians masked to the phenotypic status of the participants' samples. For 35,829 CHD cases, 44,948 controls in eight studies, we had access to individual-participant data. The eight studies were: the Bangladesh Risk of Acute Vascular Events Study,¹⁹ Copenhagen City Heart Study,²⁰ Copenhagen Ischemic Heart Disease/Copenhagen General Population Study,²⁰ European Prospective Investigation into Cancer and Nutrition-Cardiovascular Disease Study (EPIC-CVD),²¹ MONICA Risk, Genetics, Archiving, and Monograph (MORGAM) study,^{22,23} Pakistan Risk of Myocardial Infarction Study,²⁴ Pravastatin in elderly individuals at risk of vascular disease (PROSPER) trial²⁵ and the West of Scotland Coronary Prevention Study²⁶ (these eight studies are collectively called the 'CHD Exome⁺ consortium'). For 15 additional studies (collectively called the 'MICAD consortium') we used similar genotyping methods to those described above but did not genotype c.109+2T>C and had access only to study-level data. We supplemented de-novo data on Val379Ala with non-overlapping consortium-level results from a further 35,735 CHD patients and 73,481 controls in the transatlantic Coronary Artery Disease Genome-wide Replication and Meta-analysis²⁷ and Coronary Artery Disease Genetics²⁸ consortia (Table 1). We obtained tabular data on Val279Phe from seven East Asian studies involving a total of 10,088 CHD cases and 15,199 controls, identified through systematic review (text and Table 5 in Supplementary Material online). About 90% of CHD patients in our genetic analysis had myocardial infarction or other major acute coronary events; the remainder had angiographic evidence alone (e.g. >50% coronary stenosis; Supplementary Tables 2 and 5).

Lp-PLA₂ activity. For 13,835 participants, we had information on functional variants in *PLA2G7* and Lp-PLA₂ activity, using data from de-novo genotyping in MORGAM^{22,23} and PROSPER,²⁵ supplemented by published data from the CHARGE Consortium (i.e. from the Atherosclerosis Risk in Communities study,²⁹ Cardiovascular Health Study,¹⁷ Framingham Heart Study¹⁷ and Rotterdam study,¹⁷ and from 12 East Asian studies identified through the systematic review described above (Table 1; Supplementary Material text, Figure 1 and Tables 2 and 3).

Conventional cardiovascular risk factors. For 177,343 participants, we had information on functional variants in *PLA2G7* and conventional cardiovascular risk factors and several other traits, including circulating concentrations of LDL-cholesterol, high-density lipoprotein (HDL)-cholesterol, triglycerides, glucose,

insulin and C-reactive protein, and values of systolic and diastolic blood pressure, body-mass index and estimated glomerular filtration rate. Again, we supplemented data from our de-novo genotyping, with information from existing global genetics consortia (Table 1; Supplementary Tables 2 to 4).

Randomized trials of darapladib

To compare genetic associations with effects of pharmacological Lp-PLA₂ inhibition, we conducted a systematic review to identify randomized placebo-controlled trials of darapladib that had reported on Lp-PLA₂ activity, conventional risk factors and/or CHD events (Supplementary Material). CHD events in the trials were defined as fatal CHD, myocardial infarction or urgent revascularization, as recorded in STABILITY (Stabilization of Atherosclerotic Plaque by Initiation of Darapladib Therapy) and in SOLID-TIMI 52 (Stabilization of Plaque Using Darapladib-Thrombolysis in Myocardial Infarction 52).^{6,7} We pooled results across trials by fixed-effect inverse-variance weighted meta-analysis (Supplementary Figures 2 and 3; see Supplementary text for details of the methods used).

Statistical methods

We defined effect alleles as those associated with lower Lp-PLA₂ activity and assumed an additive model. For participant-level data, we assessed associations of Lp-PLA₂-lowering alleles with CHD using the genome-wide efficient mixed model analysis, an approach that models each genetic variant as a fixed-effect, but includes both fixed-effect and random-effects of genetic inheritance³⁰ to account for population stratification and relatedness among participants (Supplementary Material). The four rare loss-of-function variants were tested jointly within each study by counting the number of loss-of-function alleles carried by each participant. Log odds ratios and standard errors were meta-analysed across studies using fixed-effect meta-analysis. For studies contributing only study-level data, we performed a similar test by conducting a combined burden test across studies using the R package seqMeta v1.2 (<http://cran.r-project.org/web/packages/seqMeta/>).

We calculated associations of Lp-PLA₂-lowering alleles with soluble Lp-PLA₂ activity and conventional risk factors using linear regression within each study, and then combined the regression coefficients using fixed-effect meta-analysis. When data were missing, we used information on rs1805018 as a proxy for Val279Phe and information on rs7756935 or rs3799277 as proxies for Val379Ala (Supplementary Material). To account for population stratification,

we adjusted for the first principal component of ancestry (Supplementary Material). We calculated risk ratios for CHD with decrements in Lp-PLA₂ activity, dividing the log transformed risk ratio and confidence interval (CI) by the effect on Lp-PLA₂ activity of the instrument (i.e. the genetic variant).³¹ We investigated heterogeneity using the I^2 statistic. We used Stata 13.1.

Results

Of the 261,950 total participants in this analysis, we studied 195,715 individuals of European ancestry, 34,221 individuals of South Asian ancestry and 32,014 individuals of East Asian ancestry. In people of European or South Asian ancestry without CHD, the frequency of alleles in *PLA2G7* that lower Lp-PLA₂ activity was 0.005% at c.109+2T>C, 0.04% at Arg82His, 0.04% at Val279Phe and 0.025% at Gln287Ter (i.e. in aggregate, 0.2% of the European or South Asian participants in the current study carried one of these loss-of-function alleles, although no one carried more than one of these variants), and about 80% at Val379Ala. In people of East Asian ancestry without CHD, the frequency of Val279Phe was about 15% and about 2% of the individuals were homozygous carriers of the 279Phe allele.

Soluble Lp-PLA₂ activity

Compared with non-carriers, homozygote carriers of the 279Phe allele had 94% lower Lp-PLA₂ activity ($p < 10^{-300}$). For each 279Phe allele inherited, Lp-PLA₂ activity decreased by 45% (1.59 SD, 95% CI: 1.61–1.57; $p < 10^{-300}$). In Europeans who inherited any one of the four rare Lp-PLA₂ loss-of-function alleles, Lp-PLA₂ activity decreased by 64% (2.25 SD, 2.68–1.83; $p = 1.6 \times 10^{-25}$). For each 379Ala allele inherited, Lp-PLA₂ activity decreased by 2.7% (0.096 SD, 0.122–0.069; $p = 1.9 \times 10^{-12}$). By comparison, 160 mg once-daily darapladib reduced Lp-PLA₂ activity by 65% (2.26 SD, 2.31–2.21; $p < 10^{-300}$). Study-level estimates are provided in Supplementary Figure 2.

Cardiovascular risk factors

None of the Lp-PLA₂-related variants we studied was significantly associated with values of LDL-cholesterol, HDL-cholesterol, triglycerides, systolic or diastolic blood pressure, body-mass index, estimated glomerular filtration rate, glucose, insulin and C-reactive protein (Figure 2). By comparison, in previous randomized placebo-controlled trials, darapladib did not significantly affect concentrations of LDL-cholesterol or log triglycerides, but could have slightly increased systolic blood pressure and HDL-cholesterol values and

slightly decreased C-reactive protein concentration (Figure 2).

Clinical CHD outcomes

Compared with non-carriers, the odds ratio for CHD was 0.99 (0.95–1.03) in 279Phe heterozygotes, and 0.93 (0.82–1.05) in 279Phe homozygotes (i.e. nearly complete loss of Lp-PLA₂ function: Figure 3). For each loss-of-function (279Phe) allele inherited, the odds ratio for CHD was 0.97 (0.91–1.02; $I^2 = 30\%$; $p_{\text{Heterogeneity}} = 0.2$). In Europeans and South Asians who inherited one of the four rare Lp-PLA₂-loss-of-function alleles, the odds ratio for CHD was 0.92 (0.74–1.16; $I^2 = 0\%$; $p_{\text{Heterogeneity}} = 0.8$; Figure 3). For each 379Ala allele inherited, the odds ratio for CHD was 1.00 (0.98–1.02; $I^2 = 0.0\%$; $p_{\text{Heterogeneity}} = 0.5$; Figure 3). Study-level results are provided in Supplementary Figure 3. In sensitivity analyses, odds ratios with each loss-of-function variant were similar to the odds ratio that combined information across the four loss-of-function variants we studied. There was no evidence of heterogeneity in odds ratios between European and South Asian ancestry populations (Supplementary Figure 4).

Genetic risk ratios for CHD per 65% lower Lp-PLA₂ activity (i.e. the reduction achievable with darapladib treatment) were: 0.95 (0.88–1.03) with Val279Phe in East Asians; and 0.92 (0.74–1.16) with carriage of any one of the four rare variants studied in Europeans and South Asians; and 1.01 (0.68–1.51) with Val379Ala (Table 2). By comparison, the risk ratio for CHD with darapladib treatment (i.e. also per 65% lower Lp-PLA₂ activity) was 0.95 (0.89–1.02; Table 2).

Discussion

In a large-scale analysis of human genetic data, we tested whether Lp-PLA₂ enzyme activity is causally relevant to CHD by studying five functional alleles that produce widely differing (i.e. small, moderate or large) degrees of reduction in Lp-PLA₂ activity. We found that none was related to CHD risk, suggesting that Lp-PLA₂ enzyme activity is unlikely to be causally relevant to CHD, a conclusion concordant with results from two phase 3 trials of a pharmacological Lp-PLA₂ enzyme inhibitor.

Three features of our study merit comment. First, we studied almost 20 times more CHD patients than the previous largest study of loss-of-function *PLA2G7* alleles, thereby providing the first robust genetic evaluation of effect sizes of Lp-PLA₂ inhibition relevant to phase 3 trials such as relative risk reductions for CHD of 20%. For example, for the Val279Phe variant we had >99% power to detect a 20% risk reduction in

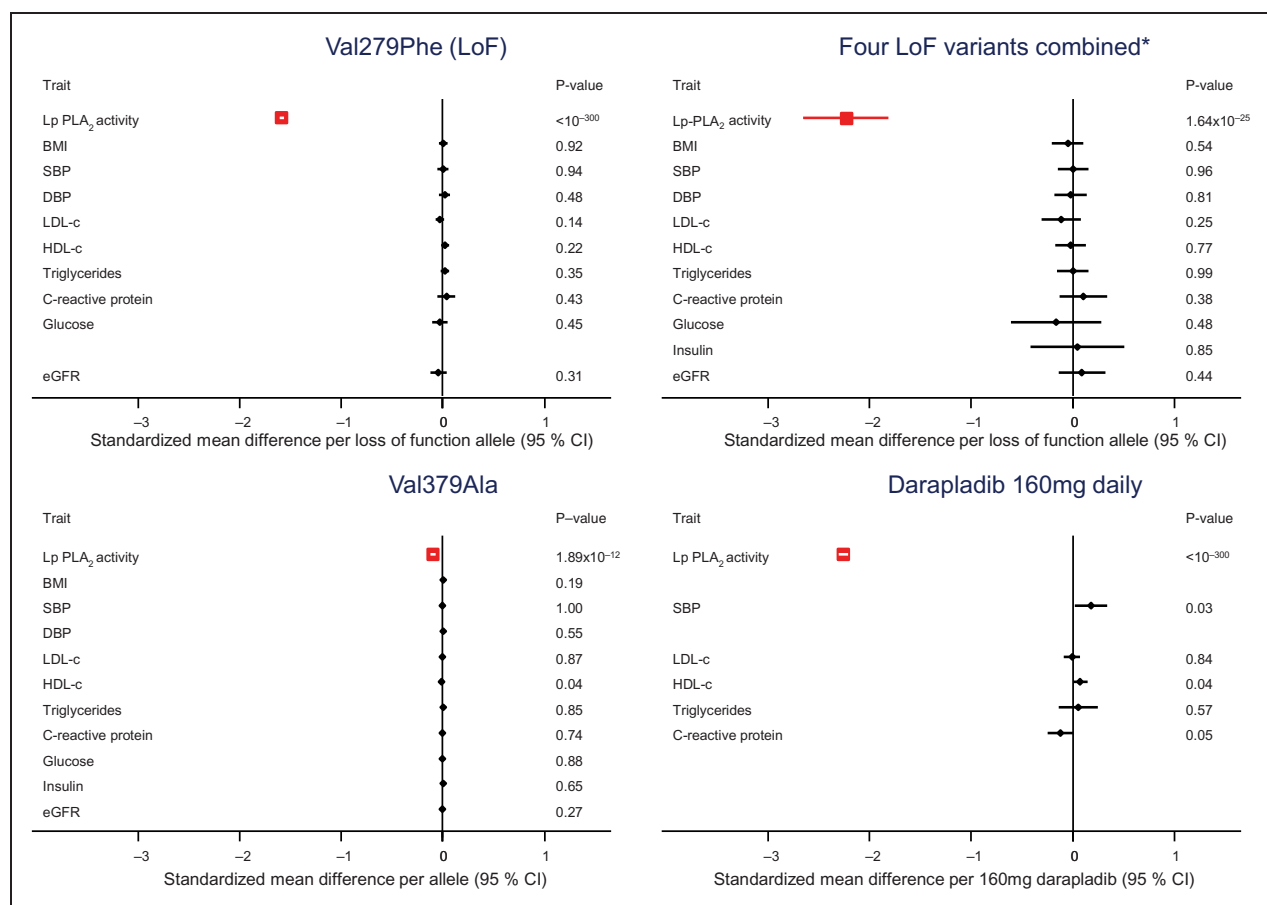


Figure 2. Mean per allele differences in Lp-PLA₂ activity and cardiovascular risk factor levels by Lp-PLA₂-lowering alleles or with darapladib 160 mg daily.

To enable comparison of the magnitude of associations across several different markers, analyses were undertaken with standardized units of measurement for each marker. Associations are presented as per allele change in the biomarker expressed as standard deviations. Numbers of participants are provided in Table 1. Details of contributing studies are provided in Supplementary Material Tables 2 and 3 online.

*Carriage of any of the four loss-of-function variants c.109+2T>C, Arg82His, Val279Phe, Gln287Ter.

BMI: body-mass index; CI: confidence interval; DBP: diastolic blood pressure; eGFR: estimated glomerular filtration rate; HDL-c: high-density lipoprotein cholesterol; LDL: low-density lipoprotein cholesterol; LoF: loss-of-function; Lp-PLA₂: lipoprotein associated phospholipase A₂; SBP: systolic blood pressure

CHD for a 65% genetic reduction in Lp-PLA₂ activity (i.e. an effect on Lp-PLA₂ activity similar to that achieved by darapladib).

Second, our study has provided the first investigation in CHD of a series of functional alleles that each reduce Lp-PLA₂ function via different molecular mechanisms. Specifically, we studied five different Lp-PLA₂-lowering alleles: three of the alleles were coding variants that produced different amino acid substitutions; two of the alleles produced protein truncations (one due to a nonsense mutation; the other due to a splice-site mutation). Because we observed null and broadly concordant findings for CHD risk across these alleles that each changed the enzyme in a different way (and to a different extent), we can more confidently conclude there is no material cause-and-effect relationship. By

contrast, when the initial phase 3 trial of darapladib was launched in 2008, only two of the five alleles we studied had yet been identified: data on Val379Ala, a weak effect missense variant, were inconclusive because CHD studies were under-powered;³² data on Val279Phe, a loss-of-function variant, and CHD risk were sparse and restricted to East Asian populations.

A third feature was our study's analysis of large-scale data from three different major ethnic groups: Europeans, South Asians and East Asians. This ethnic diversity enhanced the generalizability of our results.

Our study had potential limitations. To maximize comparability of CHD endpoints used in clinical trials with those used in human genetic studies, we restricted analysis of phase 3 darapladib trials to

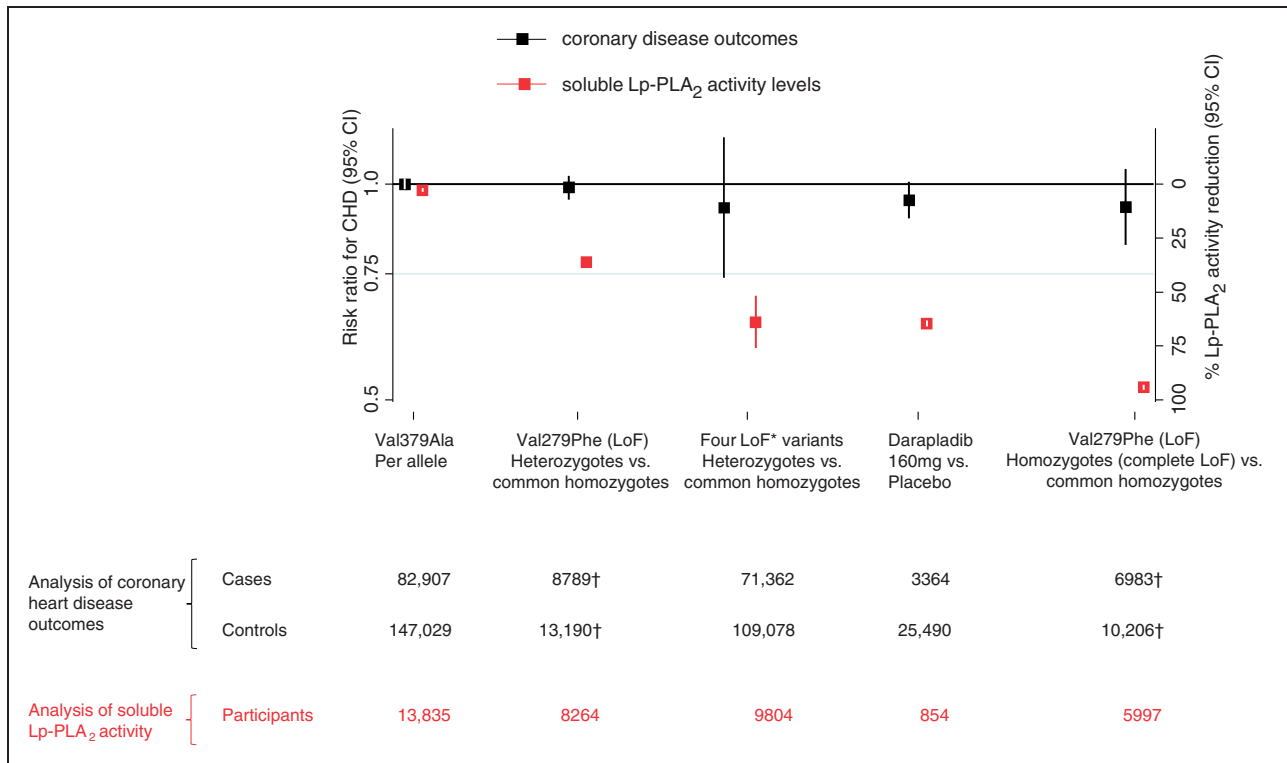


Figure 3. Association of Lp-PLA₂-lowering alleles with Lp-PLA₂ activity and CHD risk.

Spectrum of functional alleles in *PLA2G7* and effects on Lp-PLA₂ activity (red estimates) and coronary heart disease risk (black estimates);

*Carriage of any of the four loss-of-function variants c.109+2T>C, Arg82His, Val279Phe, Gln287Ter.

†One study did not provide tabular data to enable calculation of CHD odds ratios in heterozygotes or homozygotes. Hence, numbers are less than those presented for the per allele analysis in Table 2.

CHD: coronary heart disease; CI: confidence interval; LoF: loss-of-function; Lp-PLA₂: lipoprotein associated phospholipase A₂.

‘major coronary events’ and principally focused in human genetic studies on the cognate endpoints of myocardial infarction or other major acute coronary events (which constituted ~90% of the outcomes). Nevertheless, although the CHD definitions used in trials and genetic studies were similar, they were not identical.

It could be that cardioprotective benefits of Lp-PLA₂ inhibition were obscured by pleiotropic effects of *PLA2G7* variants; for example, 279Phe is known to produce a misfolded version of Lp-PLA₂ not secreted by cells, prompting suggestions that its carriage could produce ‘off-target’ effects such as increased cell death.^{33,34} However, because we found null associations between four other functional alleles in *PLA2G7* and CHD, each of which operates via a different molecular mechanism, it argues against this explanation. On the other hand, it is possible that darapladib may have additional effects beyond Lp-PLA₂ inhibition. For example, darapladib may have had slight effects on CRP levels and systolic blood pressure, which we did not observe with the genetic variants.

Lifelong genetic reductions in Lp-PLA₂ could result in compensatory responses that increase CHD risk. However, this explanation seems unlikely because it would require any such compensation to apply similarly across alleles that produce widely differing degrees of reduction in Lp-PLA₂ activity. Furthermore, any such compensation could not operate through known cardiovascular mechanisms because we observed no associations between Lp-PLA₂-lowering alleles and several established and emerging cardiovascular risk factors.

Soluble enzyme activity could be an imperfect indicator of the relevance of Lp-PLA₂ to atherosclerotic plaques. However, for homozygote carriers of 279Phe, Lp-PLA₂ activity should be almost abolished across all tissues. Finally, we studied life-long genetic reductions in Lp-PLA₂ activity in relation to first-onset CHD outcomes rather than recurrent CHD, whereas darapladib trials studied recurrent coronary events in patients with stable or acute coronary disease.

The current data underscore the growing importance of human genetic approaches to enhance the efficiency

Table 2. Comparison on a common scale of human genetic and randomized trial evidence for Lp-PLA₂ lowering and CHD.

	CHD patients	Controls	Risk ratio for CHD per 65% lower Lp-PLA ₂ activity (95% CI)
Genetically lowered Lp-PLA ₂			
Val279Phe (East Asian LoF variant)	10,088	15,199	0.95 (0.88–1.03)
Four loss-of-function variants ^a	71,362	109,078	0.92 (0.74–1.16)
Val379Ala	82,907	147,029	1.01 (0.68–1.51)
Pharmacologically lowered Lp-PLA ₂			
Darapladib	3364	25,490	0.95 (0.89–1.02)

^aCarriage of any of the four loss-of-function variants c.109+2T>C, Arg82His, Val279Phe, Gln287Ter.

CHD: coronary heart disease; CI: confidence interval; LoF: loss-of-function; Lp-PLA₂: lipoprotein associated phospholipase A₂

of development of medicines by validating (or invalidating) novel drug targets.^{35–38} Specifically, despite beneficial effects of darapladib on surrogate markers (e.g. intravascular imaging) of coronary atherosclerosis in pre-clinical and clinical studies,^{39–41} these effects did not translate into reduced outcomes in the large phase 3 studies. Hence, human genetic studies may be useful in influencing prioritization of clinical outcome trials in the future.

Our results also illustrate how human genetic evidence can assist interpretation of observational epidemiological data. For example, we found that functional alleles in *PLA2G7* do not alter levels of pro-atherogenic lipids (e.g. LDL-cholesterol), suggesting that such pro-atherogenic lipids do not mediate associations between Lp-PLA₂ activity and CHD and supporting the need to adjust epidemiological associations of Lp-PLA₂ activity with CHD risk for pro-atherogenic lipids (an approach which yields results consistent with non-causality).³

In summary, we found that none of a series of Lp-PLA₂-lowering alleles was related to CHD risk, suggesting that Lp-PLA₂ is unlikely to be a causal risk factor in CHD.

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Author contribution

ASB, DFF, JD, JMG contributed to the conception or design of the work. DFF, JMG and JD drafted the manuscript. ASB, JD, JMM, JMMH, JS, PG, PS, PW, SBu, SGT and SKap critically revised the manuscript. All the other authors contributed to the acquisition, analysis, or interpretation of data for the work. All gave final approval and agree to be accountable for all aspects of work ensuring integrity and accuracy. JMG, DFF, DS, JMMH, EDA, ASB and JD made equal contribution.

Declaration of conflicting interests

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References

1. Corson MA. Darapladib: An emerging therapy for atherosclerosis. *Ther Adv Cardiovasc Dis* 2010; 4: 241–248.
2. Awan Z and Genest J. Inflammation modulation and cardiovascular disease prevention. *Eur J Prev Cardiol* 2015; 22: 719–733.
3. Thompson A, Gao P, Orfei L, et al. Lipoprotein-associated phospholipase A(2) and risk of coronary disease, stroke, and mortality: Collaborative analysis of 32 prospective studies. *Lancet* 2010; 375: 1536–1544.
4. Jang Y, Waterworth D, Lee JE, et al. Carriage of the V279F null allele within the gene encoding Lp-PLA₂ is protective from coronary artery disease in South Korean males. *PLoS One* 2011; 6: e18208.
5. Yamada Y, Yoshida H, Ichihara S, et al. Correlations between plasma platelet-activating factor acetylhydrolase (PAF-AH) activity and PAF-AH genotype, age, and atherosclerosis in a Japanese population. *Atherosclerosis* 2000; 150: 209–216.

6. O'Donoghue ML, Braunwald E, White HD, et al. Effect of darapladib on major coronary events after an acute coronary syndrome: The SOLID-TIMI 52 randomized clinical trial. *JAMA* 2014; 312: 1006–1015.
7. White HD, Held C, Stewart R, et al. Darapladib for preventing ischemic events in stable coronary heart disease. *N Engl J Med* 2014; 370: 1702–1711.
8. UniProt Consortium. UniProt: A hub for protein information. *Nucleic Acids Res* 2015; 43: D204–D212.
9. Lek M, Karczewski KJ, Minikel EV, et al. Analysis of protein-coding genetic variation in 60,706 humans. *Nature* 2016; 536: 285–291.
10. Kruse S, Mao XQ, Heinzmann A, et al. The Ile198Thr and Ala379Val variants of plasmatic PAF-acetylhydrolase impair catalytical activities and are associated with atopy and asthma. *Am J Hum Genet* 2000; 66: 1522–1530.
11. Tjoelker LW, Eberhardt C, Unger J, et al. Plasma platelet-activating factor acetylhydrolase is a secreted phospholipase A2 with a catalytic triad. *J Biol Chem* 1995; 270: 25481–25487.
12. Yamada Y and Yokota M. Loss of activity of plasma platelet-activating factor acetylhydrolase due to a novel Gln281→Arg mutation. *Biochem Biophys Res Commun* 1997; 236: 772–775.
13. Song K, Nelson MR, Aponte J, et al. Sequencing of Lp-PLA2-encoding PLA2G7 gene in 2000 Europeans reveals several rare loss-of-function mutations. *Pharmacogenomics J* 2012; 12: 425–431.
14. Abecasis GR, Auton A, Brooks LD, et al. An integrated map of genetic variation from 1,092 human genomes. *Nature* 2012; 491: 56–65.
15. Tennessen JA, Bigham AW, O'Connor TD, et al. Evolution and functional impact of rare coding variation from deep sequencing of human exomes. *Science* 2012; 337: 64–69.
16. Stafforini DM, Satoh K, Atkinson DL, et al. Platelet-activating factor acetylhydrolase deficiency. A missense mutation near the active site of an anti-inflammatory phospholipase. *J Clin Invest* 1996; 97: 2784–2791.
17. Grallert H, Dupuis J, Bis JC, et al. Eight genetic loci associated with variation in lipoprotein-associated phospholipase A2 mass and activity and coronary heart disease: Meta-analysis of genome-wide association studies from five community-based studies. *Eur Heart J* 2012; 33: 238–251.
18. Nikpay M, Goel A, Won HH, et al. A comprehensive 1,000 Genomes-based genome-wide association meta-analysis of coronary artery disease. *Nat Genet* 2015; 47: 1121–1130.
19. Chowdhury R, Alam DS, Fakir II, et al. The Bangladesh Risk of Acute Vascular Events (BRAVE) study: Objectives and design. *Eur J Epidemiol* 2015; 30: 577–587.
20. Kamstrup PR, Tybjaerg-Hansen A, Steffensen R, et al. Genetically elevated lipoprotein(a) and increased risk of myocardial infarction. *JAMA* 2009; 301: 2331–2339.
21. Danesh J, Saracci R, Berglund G, et al. EPIC-Heart: The cardiovascular component of a prospective study of nutritional, lifestyle and biological factors in 520,000 middle-aged participants from 10 European countries. *Eur J Epidemiol* 2007; 22: 129–141.
22. Evans A, Salomaa V, Kulathinal S, et al. MORGAM (an international pooling of cardiovascular cohorts). *Int J Epidemiol* 2005; 34: 21–27.
23. Kulathinal S, Karvanen J, Saarela O, et al. Case-cohort design in practice – experiences from the MORGAM Project. *Epidemiol Perspect Innov* 2007; 4: 15.
24. Saleheen D, Zaidi M, Rasheed A, et al. The Pakistan Risk of Myocardial Infarction Study: A resource for the study of genetic, lifestyle and other determinants of myocardial infarction in South Asia. *Eur J Epidemiol* 2009; 24: 329–338.
25. Caslake MJ, Packard CJ, Robertson M, et al. Lipoprotein-associated phospholipase A(2), inflammatory biomarkers, and risk of cardiovascular disease in the Prospective Study of Pravastatin in the Elderly at Risk (PROSPER). *Atherosclerosis* 2010; 210: 28–34.
26. Shepherd J, Cobbe SM, Ford I, et al. Prevention of coronary heart disease with pravastatin in men with hypercholesterolemia. West of Scotland Coronary Prevention Study Group. *N Engl J Med* 1995; 333: 1301–1307.
27. Schunkert H, König IR, Kathiresan S, et al. Large-scale association analysis identifies 13 new susceptibility loci for coronary artery disease. *Nat Genet* 2011; 43: 333–338.
28. Coronary Artery Disease (C4D) Genetics Consortium. A genome-wide association study in Europeans and South Asians identifies five new loci for coronary artery disease. *Nat Genet* 2011; 43: 339–344.
29. Polfus LM, Gibbs RA and Boerwinkle E. Coronary heart disease and genetic variants with low phospholipase A2 activity. *N Engl J Med* 2015; 372: 295–296.
30. Zhou X and Stephens M. Efficient multivariate linear mixed model algorithms for genome-wide association studies. *Nat Methods* 2014; 11: 407–409.
31. Palmer TM, Sterne JAC, Harbord RM, et al. Instrumental variable estimation of causal risk ratios and causal odds ratios in Mendelian randomization analyses. *Am J Epidemiol* 2011; 173: 1392–1403.
32. Casas JP, Ninio E, Panayiotou A, et al. PLA2G7 genotype, lipoprotein-associated phospholipase A2 activity, and coronary heart disease risk in 10 494 cases and 15 624 controls of European Ancestry. *Circulation* 2010; 121: 2284–2293.
33. Schröder M and Kaufman RJ. The mammalian unfolded protein response. *Annu Rev Biochem* 2005; 74: 739–789.
34. Zalewski A and Macphee C. Role of lipoprotein-associated phospholipase A2 in atherosclerosis: Biology, epidemiology, and possible therapeutic target. *Arterioscler Thromb Vasc Biol* 2005; 25: 923–931.
35. Kamb A, Harper S and Stefansson K. Human genetics as a foundation for innovative drug development. *Nat Biotechnol* 2013; 31: 975–978.
36. Nelson MR, Tipney H, Painter JL, et al. The support of human genetic evidence for approved drug indications. *Nat Genet* 2015; 47: 856–860.
37. Plenge RM, Scolnick EM and Altshuler D. Validating therapeutic targets through human genetics. *Nat Rev Drug Discov* 2013; 12: 581–594.
38. Stitzel NO, Won HH, Morrison AC, et al. Inactivating mutations in NPC1L1 and protection from coronary heart disease. *N Engl J Med* 2014; 371: 2072–2082.

39. Daida H, Iwase T, Yagi S, et al. Effect of darapladib on plasma lipoprotein-associated phospholipase A2 activity in Japanese dyslipidemic patients, with exploratory analysis of a PLA2G7 gene polymorphism of Val279Phe. *Circ J* 2013; 77: 1518–1525.
40. Mohler 3rd ER, Ballantyne CM, Davidson MH, et al. The effect of darapladib on plasma lipoprotein-associated phospholipase A2 activity and cardiovascular biomarkers in patients with stable coronary heart disease or coronary heart disease risk equivalent: The results of a multicenter, randomized, double-blind, placebo-controlled study. *J Am Coll Cardiol* 2008; 51: 1632–1641.
41. Serruys PW, Garcá-Garcá HM, Buszman P, et al. Effects of the direct lipoprotein-associated phospholipase A(2) inhibitor darapladib on human coronary atherosclerotic plaque. *Circulation* 2008; 118: 1172–1182.
42. Randall JC, Winkler TW, Kutalik Z, et al. Sex-stratified genome-wide association studies including 270,000 individuals show sexual dimorphism in genetic loci for anthropometric traits. *PLoS Genet* 2013; 9: e1003500.
43. Ehret GB, Munroe PB, Rice KM, et al. Genetic variants in novel pathways influence blood pressure and cardiovascular disease risk. *Nature* 2011; 478: 103–109.
44. Willer CJ, Schmidt EM, Sengupta S, et al. Discovery and refinement of loci associated with lipid levels. *Nat Genet* 2013; 45: 1274–1283.
45. Dehghan A, Dupuis J, Barbalic M, et al. Meta-analysis of genome-wide association studies in >80 000 subjects identifies multiple loci for C-reactive protein levels. *Circulation* 2011; 123: 731–738.
46. Dupuis J, Langenberg C, Prokopenko I, et al. New genetic loci implicated in fasting glucose homeostasis and their impact on type 2 diabetes risk. *Nat Genet* 2010; 42: 105–116.
47. Pattaro C, Köttgen A, Teumer A, et al. Genome-wide association and functional follow-up reveals new loci for kidney function. *PLoS Genet* 2012; 8: e1002584.