ESC European Society of Cardiology

Cardiovascular Research (2021) **117**, 600–612
doi:10.1093/cvr/cvaa045

Genome-wide association study on coronary artery disease in type 1 diabetes suggests beta-defensin 127 as a risk locus

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Received 3 July 2019; revised 20 December 2019; editorial decision 12 February 2020; accepted 17 February 2020; online publish-ahead-of-print 20 February 2020

Time for primary review: 28 days

Aims Diabetes is a known risk factor for coronary artery disease (CAD). There is accumulating evidence that CAD pathogenesis differs for individuals with type 1 diabetes (T1D). However, the genetic background has not been extensively studied. We aimed to discover genetic loci increasing CAD susceptibility, especially in T1D, to examine the function of these discoveries and to study the role of the known risk loci in T1D.

Methods and results We performed the largest genome-wide association study to date for CAD in T1D, comprising 4869 individuals with T1D (cases/controls: 941/3928). Two loci reached genome-wide significance, rs1970112 in *CDKN2B-AS1* [odds ratio (OR) = 1.32, $P = 1.50 \times 10^{-8}$], and rs6055069 on *DEFB127* promoter (OR = 4.17, $P = 2.35 \times 10^{-9}$), with consistent results in survival analysis. The *CDKN2B-AS1* variant replicated ($P = 0.04$) when adjusted for diabetic kidney disease in three additional T1D cohorts (cases/controls: 434/3123). Furthermore, we explored the function of the lead discoveries with a cardio-phenome-wide analysis. Among the eight suggestive loci ($P < 1 \times 10^{-6}$), rs70962766 near *B3GNT2* associated with central blood pressure, rs1344228 near *CNTNAP5* with intima media thickness, and rs2112481 on *GRAMD2B* promoter with serum leucocyte concentration. Finally, we calculated genetic risk scores for individuals with T1D with the known susceptibility loci. General population risk variants were modestly but significantly associated with CAD also in T1D ($P = 4.21 \times 10^{-7}$).

Conclusion While general population CAD risk loci had limited effect on the risk in T1D, for the first time, variants at the *CDKN2B-AS1* locus were robustly associated with CAD in individuals with T1D. The novel finding on β-defensin *DEFB127* promoter provides a link between diabetes, infection susceptibility, and CAD, although pending on future confirmation.

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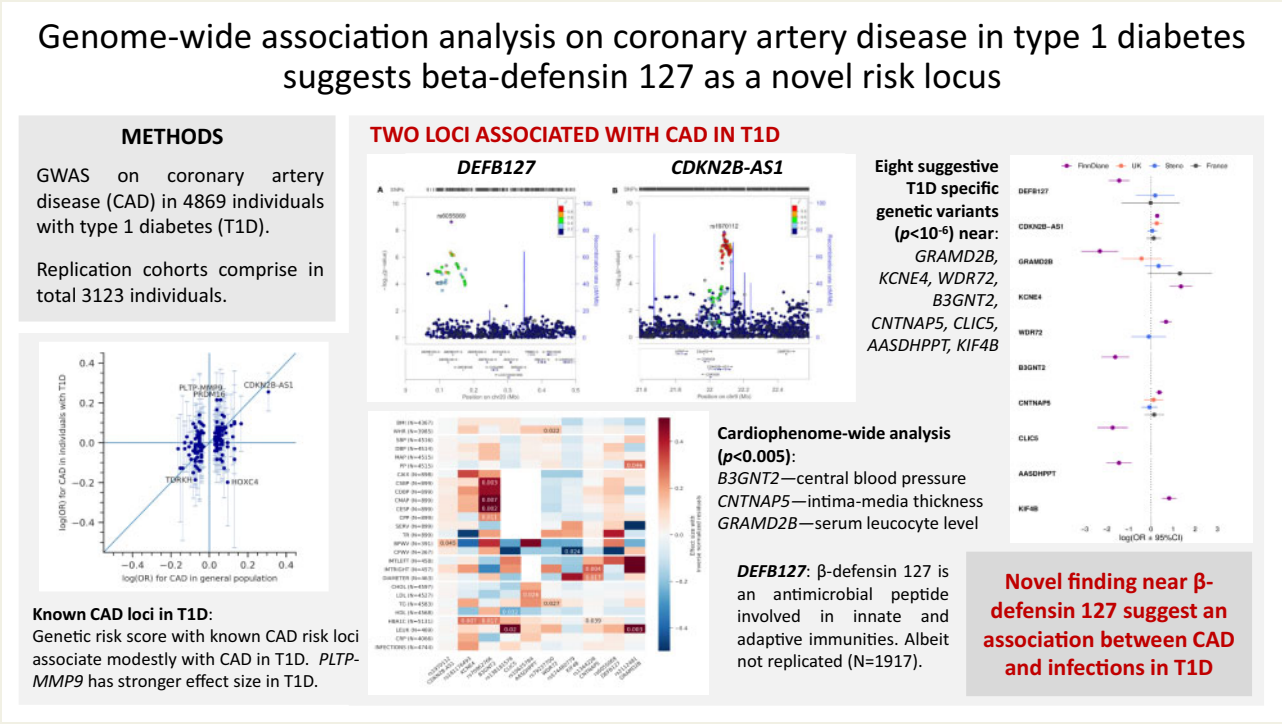
Graphical Abstract



Keywords Coronary artery disease • Type 1 diabetes • Genetics • Genome-wide association study • Cardiovascular disease

1. Introduction

A total of 425 million people worldwide have diabetes.[1] One-third of them develop diabetic complications including diabetic kidney disease (DKD), blindness, amputations, and cardiovascular disease (CVD), further divided into coronary artery disease (CAD), strokes, and other macrovascular complications. Cardiovascular deaths are the most common cause of mortality in individuals with diabetes,[2] and CVD occurs particularly early in life in individuals with type 1 diabetes (T1D). The risk of CVD increases steeply with the severity of DKD,[3] and as many as 40% of individuals with T1D and DKD develop CVD by the age of 40 years[4]; nevertheless, even individuals with T1D but without DKD have four times higher age-standardized incidence of CAD compared with non-diabetic individuals.[3] Altogether, there is increasing evidence that the incidence, risk factors, and even pathophysiology of CVD and CAD differ in individuals with T1D from those without diabetes, or even from those with type 2 diabetes (T2D).[5]

Classical risk factors for CAD in diabetes include unfavourable glycaemic control, high blood pressure, and dyslipidaemia.[6] With the improvements in the treatment of risk factors, the incidence of CAD has drastically decreased over the decades.[7] In addition, family history of CAD is an important risk factor both in the general population,[8] and among individuals with insulin-treated diabetes.[9] Consequently, genome-wide association studies (GWASs) have revealed 163 distinct loci for CAD in the general population.[10] While replication of these loci has been attempted also in individuals with diabetes, most of the results have been inconclusive.[11–13] A previous study suggested that CAD risk associated with the 9p21 locus is magnified in individuals with T2D in the presence of poor glycaemic control.[14] Furthermore, candidate gene studies on CAD in diabetes have suggested, e.g. haptoglobin 2-2 genotype associated with CVD specifically in diabetes, including T1D.[5] The first genome-wide association study on CAD in individuals with T2D identified variants near the glutamine synthase (*GLUL*) gene,[15] and another GWAS in the ACCORD trial revealed two loci that affected CVD mortality in the intensively treated participants with T2D.[16] A recent GWAS on CAD in 15 666 individuals with diabetes from the UK Biobank found that two of the previously identified CAD loci, the *LPA* and 9p21 regions, were genome-wide significantly associated with CAD also in individuals with diabetes, with the effect sizes similar to the general population.[17] The first GWAS on CAD in individuals with T1D, including 434 CAD cases and 3123 non-CAD patients, suggested novel susceptibility variants for CAD at *CDK18*, *FAM189A2*, and *PKD1* loci, even though these did not reach genome-wide significance in the final analysis.[13]

Due to the central role of diabetes and hyperglycaemia for the risk of CAD, an intriguing question is, whether novel genetic risk factors can be discovered in individuals with T1D, who tend to have suboptimal glycaemic control, who suffer CAD early in life, and who are known to display a differing CAD pathogenesis from individuals without diabetes or even with T2D.[5] In this work, we present the results from the largest GWAS on CAD in T1D to date.

2. Methods

2.1 Patients

2.1.1 FinnDiane study

This study included 5342 Finnish individuals with T1D from the Finnish Diabetic Nephropathy (FinnDiane) study, an ongoing nationwide multicentre study with the aim to identify factors leading to diabetic complications. The participants were diagnosed with T1D with onset age ≤40 years and insulin treatment initiated within 2 years from diagnosis if known. The individuals underwent a thorough clinical examination by the attending physician, including blood samples and timed urine collections, at their FinnDiane baseline visit; a subset of patients also participated in similar follow-up visits. Further health-related data were obtained from the patients' medical records. A subset of 740 individuals was included in FinnDiane through collaboration with the Finnish National Institute of Health and Welfare and had only medical records and registry data available.

The study protocol was approved by the ethics committee of the Helsinki and Uusimaa Hospital District (491/E5/2006, 238/13/03/00/2015, and HUS-3313-2018), and the study was performed in accordance with the Declaration of Helsinki. All participants gave informed consent before participation in the study. Summary statistics from the discovery cohort GWAS will be submitted to GRASP database.

CAD was defined as a hard CAD event by the end of 2015 based on the Finnish Death Registry and Finnish hospital discharge registry using ICD codes I21, I22, and I23 for myocardial infarctions; or procedure codes for coronary bypass surgery or coronary balloon angioplasty (Supplementary material online, *Table S1*). Controls were individuals without hard CAD events. Only 5% of cases had CAD event before age of 35 years, and thus, controls with age <35 years ($N = 322$) or diabetes duration <15 years ($N = 151$) were excluded from the case–control CAD analysis, including 4869 individuals (941 cases and 3928 controls). Among these, 2590 had normoalbuminuria, while 2113 had DKD, defined as microalbuminuria ($N = 719$), macroalbuminuria ($N = 544$), or end-stage renal disease (i.e. dialysis, kidney transplant, or estimated glomerular filtration rate <15 mL/min/1.73 m^2; $N = 850$) at the latest available data point.

2.1.2 Replication cohorts

Replication of the lead findings was performed in three studies comprising 3557 T1D individuals with (N_{cases} = 434) and without CAD ($N_{controls}$ = 3123), from France, Denmark, and UK/Republic of Ireland (UK-ROI), included in a recently published CAD GWAS meta-analysis among T1D individuals.[13]

2.2 GWAS genotyping and data processing

The genome-wide genotyping and imputation procedures have been described earlier.[18] In short, 6152 unique Finnish individuals with diabetes and their relatives were genotyped at the University of Virginia with HumanCoreExome Bead arrays 12-1.0, 12-1.1, and 24-1.0 (Illumina, San Diego, CA, USA). Genotype calling with zCall,[19] sample and variant quality control, genotype imputation with minimac3-software[20] and the 1000 Genomes phase 3 reference panel were also performed at the University of Virginia. After quality control, 6019 individuals remained; 575 of these did not have T1D and/or data on CAD, resulting in 5342 T1D individuals with CAD and GWAS data available.

2.3 Statistical methods

2.3.1 GWAS analysis

Association analysis was performed with a score test based on estimated allele dosages using Rvtest (version 20160404).[21] Calendar year of diabetes onset correlates strongly with the incidence of CAD most likely due to the improvements in diabetes management and glycaemic control. We have adjusted the analysis for the calendar year of diabetes onset (Supplementary material online, *Figure S1*), in addition to gender and genotyping batch; and for kinship matrix to account for relatedness and population substructure. The top discoveries were reanalysed with DKD as an additional adjustment covariate. Results were filtered to those in Hardy–Weinberg equilibrium ($P \geq 5 \times 10^{-8}$) with minor allele frequency (MAF) ≥0.01 and imputation quality $r^2 \geq 0.6$. Suggestive lead single-nucleotide polymorphisms (SNPs) were defined as independent SNPs [distance ≥100k base pairs (bp)] with *P*-value $<10^{-6}$.

2.3.2 Fine mapping of the loci

Fine mapping of causal variants at the lead loci was performed with FINEMAP v1.3[22] based on a stochastic search of most important causal configurations in the GWAS summary statistics. We used the default parameters and included 1 Mbp region up and downstream of each lead variant. Linkage disequilibrium structure was calculated based on the FinnDiane imputed maximum likelihood genotypic data.

2.3.3 Replication and meta-analysis

For the loci reaching *P*-value 10^{-6}, we looked for *in silico* replication in a recent GWAS for CAD in T1D patients.[13] Variants with MAF ≥ 0.01 and imputation quality $r^2 \geq 0.6$ were included in the analysis. Meta-analysis was performed for both DKD adjusted and unadjusted models with the metal software (2011-03-25 release)[23] based on effect sizes and standard errors.

2.3.4 Power calculations

Power calculations were conducted with genetic power calculator[24] using relative risks calculated from odds ratios (ORs) and assuming a 19.3% disease prevalence as observed in the FinnDiane study. Power to detect an association with $\alpha = 5 \times 10^{-8}$ significance level in the discovery cohort is approximately 80% for variants with ORs of 1.40, 1.63, and 1.90 and minor allele frequencies of 0.50, 0.10, and 0.05, respectively. Furthermore, a variant with MAF of 0.01 and OR of 3.32 can be discovered with a roughly 75% power. Replication power of the lead findings was evaluated with a 0.01 (0.05/5) significance level by assuming disease prevalence as perceived in the replication cohorts and utilizing discovery cohort lower bound ORs and effect allele frequencies (*Table 1*). Finally, power to replicate CAD loci previously discovered in T1D was evaluated with a 0.003 (0.05/16) significance level (Supplementary material online, *Table S2*), in T2D with a 0.01 (0.05/5) significance level, and in the general population with a 0.00031 (0.05/160) significance level by considering published effect allele frequencies and ORs, more precisely lower ORs when available (Supplementary material online, *Figure S2*).

2.3.5 Survival analysis

The lead genotype ($P < 10^{-6}$) effects were modelled with Cox proportional hazard (PH) models with time varying from diabetes onset until the latest follow-up data or a CAD incident. Implemented models incorporated different adjustment covariates: gender, diabetes onset year, age at onset of diabetes, and time-weighted mean HbA1c level, based on a median of 21 HbA1c measurements (maximum 142) available for 5139

Table I GWAS, replication and meta-analysis results for loci reaching $P < 10^{-6}$ in the discovery GWAS

Discovery stage							Replication			Meta-analysis			Meta-analysis with DKD adjustment[a]	
SNP	**Chr:Pos_REF/ALT**	**Gene**	**EAF**	**OR (95% CI)**	***P*-value**	**RSQ**	***N***	**Power**	***P*-value**	**Dir**	**OR (95% CI)**	***P*-value**	**OR (95% CI)**	***P*-value**
rs1970112	9:22085598_T/C	*CDKN2B-AS1*	0.41	1.32 (1.2–1.46)	1.50×10^{-8}	0.98	434/3123	0.46	0.09	+ +++	1.27 (1.17–1.38)	1.19×10^{-8}	1.28 (1.18–1.39)	1.91×10^{-9}
rs181176493	2:224157866_G/A	*TRK-TTT15-1(pseudo)*, KCNE4*[†]	0.01	3.88 (2.33–6.47)	1.98×10^{-7}	0.80	–	–	–	+ ???	3.88 (2.33–6.47)	1.98×10^{-7}	3.62 (2.19–5.98)	4.91×10^{-7}
rs70962766	2:62406999_ CTTTTTTTTTTTT/C	*RPSA26(pseudo)*, B3GNT2**	0.99	0.2 (0.11–0.37)	4.68×10^{-7}	0.64	–	–	–	- ???	0.2 (0.11–0.37)	4.68×10^{-7}	0.47 (0.29–0.75)	0.0017
rs138181578	6:45725830_A/AT	*LOC107986519*[†], *CLIC5*[†]	0.99	0.18 (0.09–0.35)	6.78×10^{-7}	0.77	–	–	–	- ???	0.18 (0.09–0.35)	6.78×10^{-7}	0.36 (0.22–0.60)	8.33×10^{-5}
rs10625784	11:106193897_T/TAAA	*LOC643855*, AASDHPPT*[†]	0.99	0.23 (0.13–0.42)	7.63×10^{-7}	0.83	–	–	–	- ???	0.23 (0.13–0.42)	7.63×10^{-7}	0.44 (0.28–0.70)	0.00045
rs79237700	15:53741612_T/C	*LOC105370826, WDR72**	0.04	1.97 (1.51–2.55)	3.86×10^{-7}	0.75	237/632	0.17	0.79	+ -??	1.82 (1.42–2.33)	2.23×10^{-6}	1.76 (1.37–2.25)	6.88×10^{-6}
rs574480779	5:154390880_TA/T	*KIF4B*	0.03	2.27 (1.64–3.15)	9.36×10^{-7}	0.69	–	–	–	+ ???	2.27 (1.64–3.15)	9.36×10^{-7}	2.14 (1.56–2.95)	2.91×10^{-6}
rs1344228	2:124286924_C/T	*LOC100422580*[†], *CNTNAP5*[‡]	0.11	1.46 (1.26–1.69)	5.64×10^{-7}	1.00	434/3123	0.33	0.71	+ -++	1.33 (1.17–1.51)	8.68×10^{-6}	1.33 (1.17–1.50)	8.30×10^{-6}
rs6055069	20:134284_T/C	*DEFB127*	0.98	0.24 (0.15–0.38)	2.35×10^{-9}	0.62	322/1917	0.95	0.74	- +?-	0.38 (0.25–0.56)	1.36×10^{-6}	0.49 (0.35–0.70)	9.80×10^{-5}
rs2112481	5:125691632_T/G	*GRAMD2B*	0.99	0.10 (0.04–0.23)	6.98×10^{-8}	0.63	434/3123	1	0.35	- +-+	0.67 (0.43–1.01)	0.058	0.73 (0.50–1.06)	0.097

-, protection; ?, data not available; +, predisposition; Chr:Pos_REF/ALT, chromosome and base pair position, reference/alternative (=non-effect/effect) allele; Dir, effect direction (for effect i.e. alternative allele) in FinnDiane, SDCC, UK-ROI, and French; EAF, effect (alternative) allele frequency; Gene, closest gene(s) underlying or within the promoter region (5kbp upstream), or *within ±50kbp, [†]within ±250kbp, or [‡]within ±500kbp; *N*, *N*cases/controls in replication; OR (95% CI), odds ratio and 95% confidence interval; Power, statistical power to observe association with $\alpha = 0.05/5 = 0.01$ significance level, based on discovery study EAF and 95% lower CI of OR, and 12.2%, 27.3%, or 14.4% CAD prevalence in corresponding replication cohort; RSQ, imputation r^2 quality estimate.

[a]$N_{FinnDaine}$ = 926/3777 in meta-analysis with DKD.

of 5342 patients. Age at diabetes onset and mean HbA1c did not fulfil the PH assumption, and thus, we stratified the HbA1c level (<6.5, 6.5–7.5, 7.5–8.5, 8.5–9.5, 9.5–10.5, 10.5–11.5, or 11.5>) and age at diabetes onset subgroups (<6.5, 6.5–10.5, 10.5–14.5, 14.5–20.5, 20.5–26.5, and 26.5>). Survival modelling, including Kaplan–Meier visualization, was performed in R statistical software with survival and survminer packages.

2.3.6 Phenotypic characterization of lead GWAS loci

Peripheral blood pressures including systolic blood pressure (SBP, $N = 4516$), diastolic blood pressure (DBP, $N = 4514$), pulse pressure (PP; SBP–DBP, $N = 4515$), and mean arterial pressure (MAP; DBP–1/3 × PP, $N = 4515$) were measured during the FinnDiane visits or obtained from medical records. In addition, examined variables included cholesterol ($N = 4597$), low-density lipoprotein (LDL, calculated with Friedewald's formula, $N = 4527$), high-density lipoprotein (HDL, $N = 4568$), and log-transformed triglyceride ($N = 4583$) concentrations; two inflammatory markers, leucocyte ($N = 469$) serum concentration and log-transformed C-reactive protein ($N = 4066$) concentration; log-transformed and averaged annual number of antibiotic purchases ($N = 4744$); body mass index ($N = 4367$) and waist to hip ratio ($N = 3985$); and the time-weighted mean HbA1c concentration ($N = 5131$). Further arterial stiffness and atherosclerosis measures collected during the FinnDiane visits of the Helsinki district were included. Arterial stiffness was measured with SphygmoCor device (Atcor Medical, Sydney, Australia) by recording peripheral measurements; and by estimating corresponding central blood pressures ($N = 899$) including central end-systolic pressure (CESP) in addition to central SBP, DBP, MAP, and PP. Furthermore, subendocardial viability ratio ($N = 899$), time to reflection ($N = 899$), central augmentation index ($N = 898$), brachial pulse wave velocity (PWV, $N = 391$), and central PWV ($N = 367$) were measured, out of which pulse wave velocities only after 2008. The amount of atherosclerotic plaque at common carotid arteries was measured with Esaote ultrasound (Esaote Artlab, Genova, Italy) revealing the diameter ($N = 463$) in addition to intima-media thicknesses of both right ($N = 457$) and left arteries ($N = 458$) (Supplementary material online, *Table S3*).

Associations between the clinical variables and GWAS lead loci ($P < 10^{-6}$) were performed with Rvtest[21] by requiring minor allele count ≥5, and adjusting for gender and diabetes onset year. Diabetes duration was restricted to a minimum of 5 years. Due to intercorrelation between the variables, only the number of SNPs was considered when correcting for multiple testing.

2.3.7 DKD interaction analysis

Interactions between the lead variants and DKD in CAD development were assessed with logistic regression in R statistical software. DKD was defined as a binary: normoalbuminuria and albuminuria/end-stage renal disease. Analyses were adjusted for genotyping batch, gender, and diabetes onset calendar year.

2.3.8 Histone modifications and chromatin interactions

Histone modification CHiP-seq data were queried for the lead loci in adult heart left ventricles and iPSC-derived cardiomyocytes in the WashU epigenome browser (http://epigenomegateway.wustl.edu/legacy/) within the 'promoter interaction map for cardiovascular disease genetics' public track.[25] Promoter Capture Hi-C (PCHiC) chromatin conformation data in hESC derived cardiomyocytes[26] were queried for lead loci using CHiCP browser (www.chicp.org).[27]

2.3.9 Polygenic risk score

We calculated a genetic risk score for CAD with general population risk variants reported by Erdmann *et al.*,[10] defined as a mean of the SNP dosages, weighted by the corresponding natural logarithm of risk allele OR from an original study (Supplementary material online, *Table S4*). Association between the genetic risk score and CAD was evaluated in R with logistic regression, and model fit was estimated with McFadden pseudo R^2.

2.3.10 Pathway analysis

Genes and genetic pathways were scored with PASCAL software.[28] Gene scoring was performed by counting sum-of-chi-squares statistics from gene regions with 50 kb up- and downstream extensions. Variants with MAF ≥ 0.01 in the 1000 Genomes project and genes with ≤3000 variants were accepted. Genes within the same pathway and 1.0 Mb distance were fused together for pathway scoring. Bonferroni corrected significance thresholds were utilized for significance indication; 5×10^{-6} for genes and 5×10^{-5} for pathways.

3. Results

3.1 Lead findings for CAD

The GWAS included 4869 individuals with T1D, out of which 941 (19%) had suffered a CAD event (*Table 2*). The mean age at the first CAD event was 52.5 [standard deviation (SD) = 10.2] years; 11% of the cases experienced the first CAD event before the age of 40 years, and for 65 (6.9%) cases, death from a cardiovascular cause was the first severe cardiovascular event. GWAS included 8 744 746 SNPs and revealed two loci that were genome-wide significantly associated ($P < 5 \times 10^{-8}$) with CAD (*Figure 1*): a common variant rs1970112 (MAF = 0.41) within an intron of the well-known *CDKN2B-AS1* locus on chromosome 9p21 [OR = 1.32, 95% confidence interval (CI) 1.2–1.46, $P = 1.50 \times 10^{-8}$], and a low frequency intergenic variant rs6055069 (MAF = 0.02) on chromosome 20 within *DEFB127* gene promoter region (OR for minor T allele 4.17, 95% CI 2.63–6.67, $P = 2.35 \times 10^{-9}$; *Figure 2*). A total of 10 loci reached a suggestive *P*-value of $<10^{-6}$ (*Table 1*). Statistical fine mapping suggested that each lead locus included only one underlying causal variant (Supplementary material online, *Table S5*); except for the chromosome 11 locus which had a 43% posterior probability to include two causal variants (Supplementary material online, *Figure S3*).

3.1.1 Survival analyses

Since the risk of CAD increases with diabetes duration,[3] we implemented survival models with various adjustment covariates for the two genome-wide significant variants. Both SNPs had significant effect sizes in all models (*Figure 3*, Supplementary material online, *Table S6*). Furthermore, the eight suggestive loci had significant genotypic effects in Cox PH models when accounting for diabetes duration and by adjusting for calendar year of diabetes onset, gender, age at diabetes onset, and mean HbA1c level (Supplementary material online, *Table S7*).

3.1.2 Adjustment with DKD status

The *CDKN2B-AS1* variant effect remained significant with a similar OR when adjusted for DKD (OR = 1.32, $P = 6.67 \times 10^{-9}$), suggesting that the locus affects CAD risk independently of DKD (Supplementary material online, *Table S8*). On the contrary, *DEFB127* variant effect size and statistical significance were attenuated when adjusting for DKD (OR = 2.70,

Table 2 Clinical characteristics of the subjects

N	Cases 941	Controls 3928	*P*-value
Males, *N* (%)	530 (56.3)	1992 (50.7)	0.0022
Diabetes onset (calendar year)	1967 ± 9.6	1979 ± 11.1	1.0×10^{-174}
Age at diabetes onset (years), median ± IQR	13.3 ± 11.7	14.3 ± 13.2	9.33×10^{-4}
Age (years)	52.5 ± 10.2	52.2±10.3	0.48
T1D duration (years)	37.4 ± 10.4	36.0±10.8	3.12×10^{-4}
Mean HbA1c (%)	8.88 ± 1.34	8.37±1.15	2.98×10^{-22}
Mean HbA1c (mmol/mol)	73.5 ± 14.7	68.0±12.6	2.98×10^{-22}
HbA1c count, median ± IQR	16 ± 28	23 ± 26	8.00×10^{-22}
Deceased by 31 December 31 2015[a]	449 (47.7%)	436 (11.1%)	2.62×10^{-150}
Cardiovascular death[b]	65 (6.9%)	0 (0%)	–
DKD [*N* cases/controls (%cases)]	689/237 (74%)	1424/2353 (38%)	2.20×10^{-16}

Values are represented as mean ± SD, or median ± IQR, or *N* (%).
DKD, micro- or macroalbuminuria or end-stage renal disease.
[a]Before 30 December 2015, including deaths after CVD event.
[b]Death of cardiovascular cause as the first CHD event.

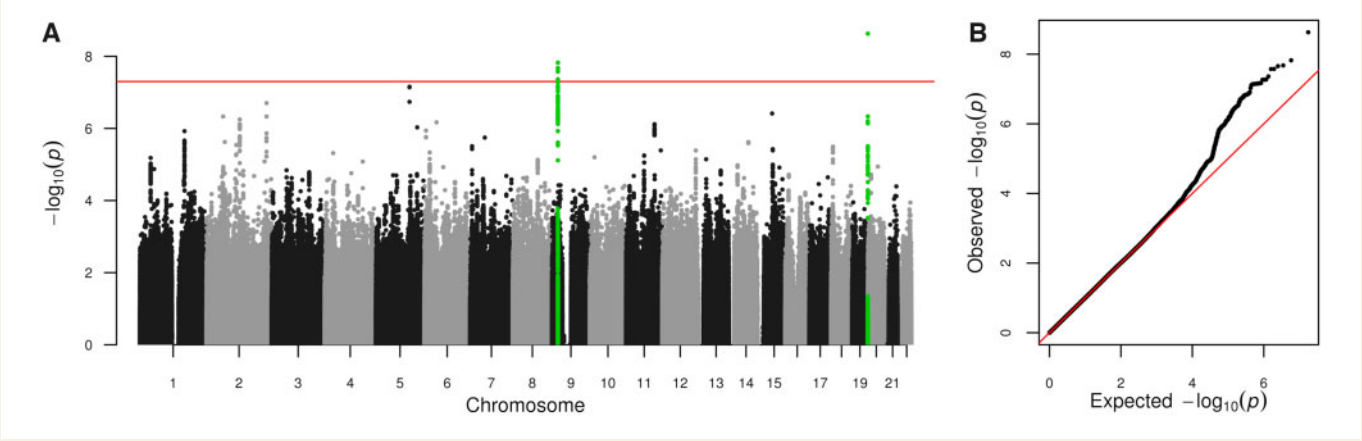


Figure 1 Manhattan plot and QQ plot of the results showing a genome-wide significant association on chromosomes 9 and 20. (*A*) Red horizontal line on the Manhattan plot illustrates the threshold for genome-wide significance, i.e. *P*-value < 5×10^{-8}. All SNPs within 100 kb of the genome-wide significant SNPs are highlighted with green. (*B*) QQ plot shows the expected vs. observed -$\log_{10}(p)$.

$P = 1.09 \times 10^{-6}$), which may reflect the high correlation between CAD and DKD in T1D, shared aetiology between DKD and CAD, or CAD due to DKD. Adjustment with DKD attenuated the association with CAD for rs70962766 near *B3GNT2* considerably ($P = 0.0018$). However, interaction terms between the variants and DKD in the development of CAD were insignificant for all lead SNPs (Supplementary material online, *Table S8*).

3.1.3 Replication

Replication of the 10 loci was attempted by adjusting for DKD as in the previous publication, as well as by reanalysing without the DKD adjustment from three independent GWAS studies on CAD in T1D, including a total of 434 cases with CAD and 3123 controls without CAD.[13] Due to low allele frequency or limited imputation quality, data were available for five of the lead SNPs in one or more replication studies. Association at the 9p21 reached $P = 0.09$ in replication without DKD adjustment. Despite the unsuccessful replication, meta-analysis across the four cohorts kept the variant genome-wide significant ($P = 1.19 \times 10^{-8}$). When adjusted for DKD, however, the 9p21 replicated ($P = 0.04$), thus improving the combined *P*-value from the meta-analysis of the three studies and our DKD adjusted statistics to $P = 1.91 \times 10^{-9}$. None of the other loci were replicated (*Table 1*, *Figure 4*). Of note, with DKD adjustment, *CNTNAP5* showcased the same direction of effect in all four cohorts. Further look-up of the 10 lead loci in GWAS data for the general population including 60 801 CAD cases and 123 504 controls was significant only for the *CDKN2B-AS1* locus (rs1970112 $P = 1.2 \times 10^{-89}$)[29] (Supplementary material online, *Table S9*).

3.2 Phenotypic characterization of the lead loci

Three of the lead loci represented association with at least one CVD predisposing phenotype ($P < 0.005$, corrected for 10 loci; *Figure 5*,

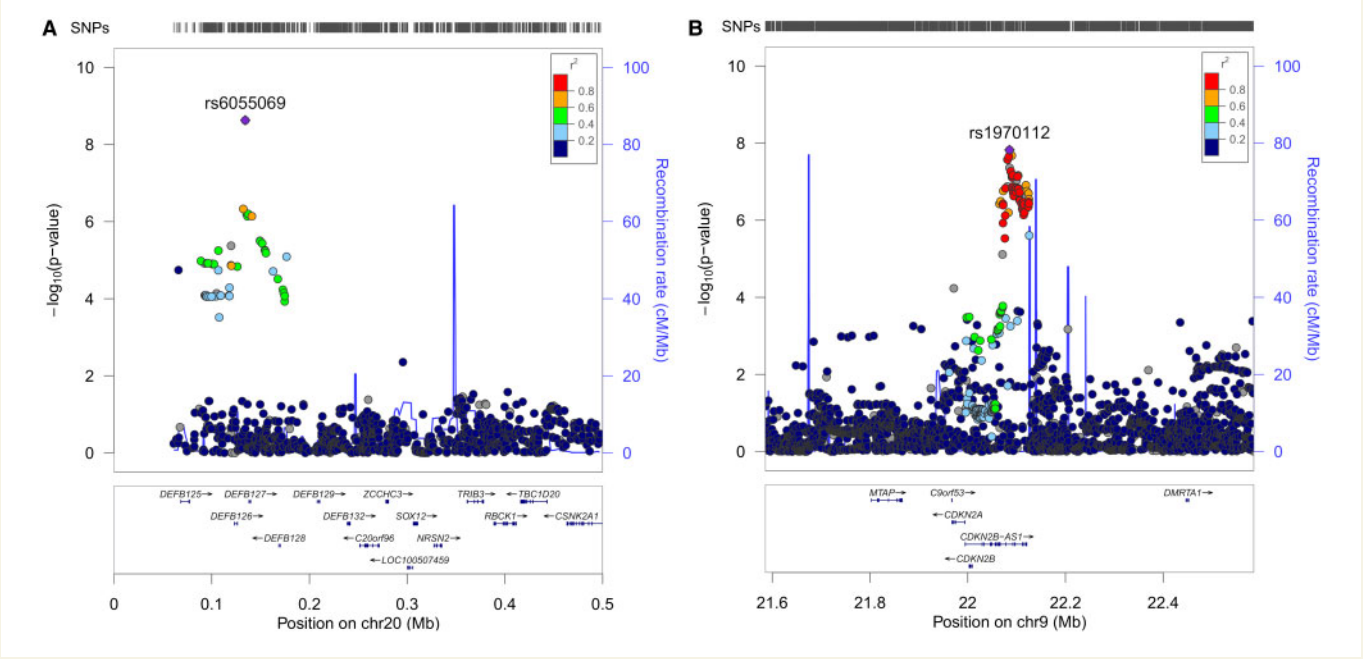


Figure 2 LocusZoom plot of the (*A*) chromosome 20 and (*B*) 9p21 regions associated with CAD. Each dot represents a SNPs, with chromosomal position (bp) given on the *x*-axis, and statistical significance (-$\log_{10}$(*p*-value)) on the *y*-axis. Dot colour indicates the linkage disequilibrium with the SNP with the smallest *P*-value, marked with purple diamond.

Supplementary material online, *Table S10*), thus, elucidating their potential roles in the pathogenesis. rs70962766 near *B3GNT2* was associated with central SBP and CESP, and nominally ($P < 0.05$) with multiple other arterial stiffness measures. rs1344228 near *CNTNAP5* locus was associated with intima media thickness ($P < 0.005$), a strong indicator of vascular disease.[30] In addition, both rs70962766 and rs1344228 were nominally associated with increased HbA1c ($P < 0.05$). The variant rs2112481 near *GRAMD2B* was associated with serum leucocyte level ($P < 0.005$), thus possibly acting by inducing inflammation, and nominally with PP. The lead variant at *CDKN2B-AS1* was nominally associated with brachial PWV ($P < 0.05$). Arterial stiffness, measured as PWV and characterized by decreased elastic properties of the vessels, precedes hypertension.[31]

3.3 Association with gene expression and epigenetic interactions

3.3.1 Expression quantitative trait loci

Associations between the lead loci and gene expression levels at different tissues were inspected from the Genotype-Tissue Expression (GTEx) portal comparing whole-genome sequencing genotypes of the study participants to tissue-specific RNA-seq gene expression levels. The rs1970112 at *CDKN2B-AS1* was the only locus with significant expression quantitative trait loci (eQTL) associations. The risk allele was associated with increased *CDKN2B* expression in brain cortex (normalized effect size; NES = 0.36) in addition to decreased expression in sigmoid colon (NES = -0.29), minor salivary gland (NES = -0.21), and tibial nerve (NES = -0.15) after correcting for the number of tissues ($P_{eQTL} < 0.001$). Of note, no *DEFB127* expression was detected in GTEx eQTL tissues, possibly explaining the lack of eQTL associations.

3.3.2 Histone modifications and chromatin interactions

Three of the lead SNPs were located within the promoter region defined as 5kbp upstream of a protein coding gene transcription start site, including rs6055069 4kbp upstream of *DEFB127*, rs2112481 4kb upstream of *GRAMD2B*, and rs574480779 2kbp upstream of *KIF4B*. Each of these three SNPs overlapped a left ventricle histone H3K27ac peak,[25] typically found on promoters or enhancers of active genes, thus providing further support for the *DEFB127*, *GRAMD2B* and *KIF4B* as the target genes (Supplementary material online, *Table S10*). Furthermore, chromatin conformation data on hESC derived cardiomyocytes[26] showed interaction between the rs2112481 containing DNA fragment and *GRAMD2B* and *ALDH7A1* genes, suggesting that the variant affects the transcription of the two genes (Supplementary material online, *Table S10*).

3.4 CAD loci in the general population

In the general population, GWAS have successfully revealed a total of 163 CAD susceptibility loci.[10] Out of the 156 variants available in our GWAS, only the *CDKN2B-AS1* variant was significant after Bonferroni correction, with a similar effect size as in the general population (*Figure 6*, Supplementary material online, *Table S4*). Furthermore, rs3827066 with *PLTP* and *MMP9* as the most likely target genes[10] showcased a stronger effect size for CAD in T1D [OR = 1.24 (1.08–1.42)] than in the general population [OR = 1.04 (1.03–1.06)],[32] with significant heterogeneity in meta-analysis (I^2 = 84.5%, $P = 0.011$). There were two other variants with significantly higher effect sizes in T1D as well as 11 variants with significantly higher effect sizes in the general population. Of note, we had low power to replicate many of the loci (Supplementary material online, *Figure S2*). However, the genetic risk score based on the general population CAD risk variants was significantly associated with CAD also in T1D [$P = 2.74 \times 10^{-8}$, OR per 0.005 unit increase 1.37 (1.23–1.54)] although with limited model fit (R^2 = 0.0065); individuals with CAD had slightly

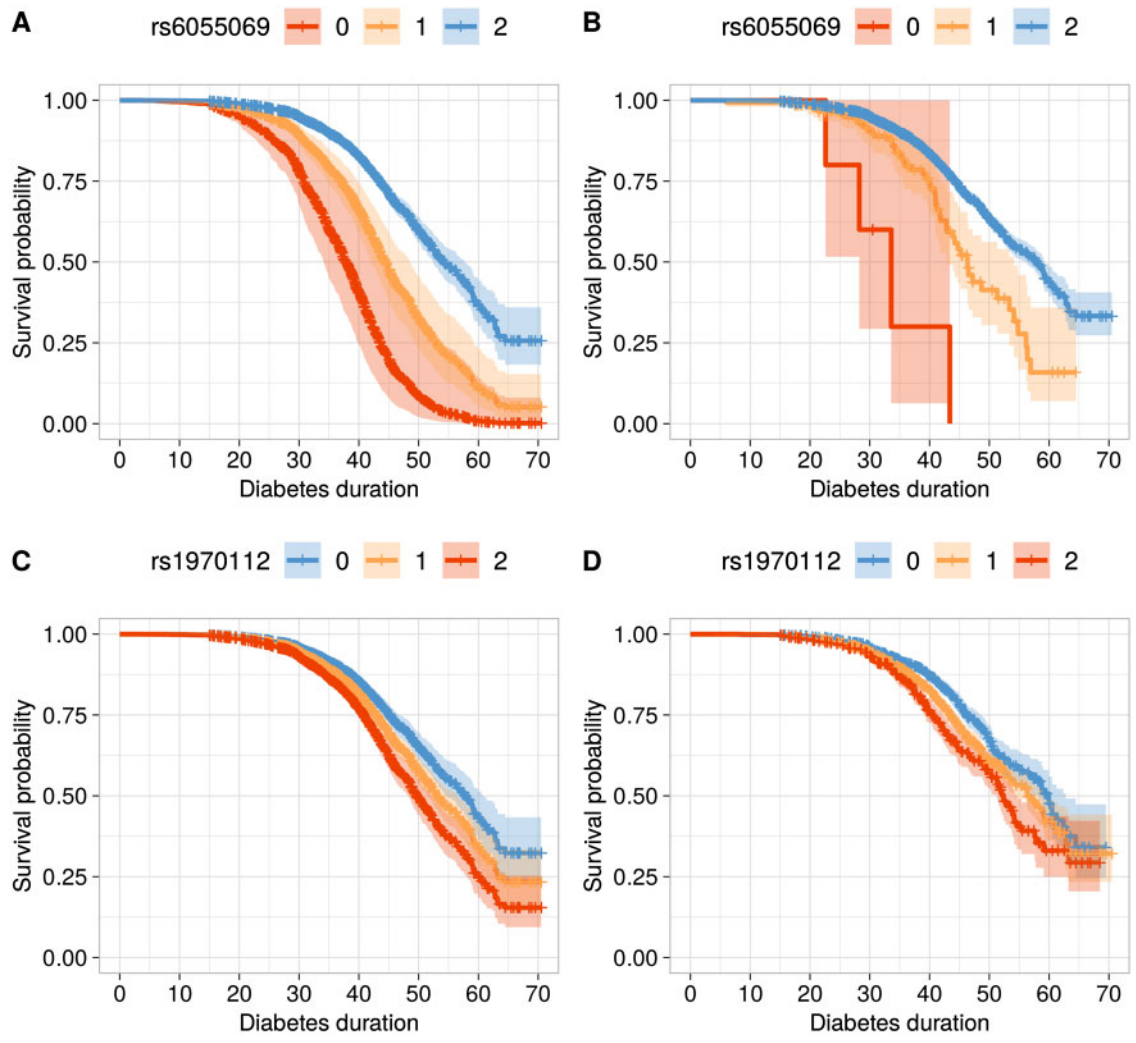


Figure 3 Predicted survivor functions of Cox proportional hazards models and Kaplan–Meier survival estimators grouped according to most likely genotypes. (*A*) Cox PH survivor function of rs6055059 (*DEFB127*) with *P*-value 8.64×10^{-8}, adjusted for gender and calendar year of diabetes onset ($N = 4869$), (*B*) Kaplan–Meier estimator of rs6055059 (*DEFB127*), (*C*) Cox PH survivor function of rs1970112 (*CDKN2B-AS1*) with *P*-value 4.13×10^{-8}, adjusted for gender and calendar year of diabetes onset ($N = 4869$), and (*D*) Kaplan–Meier estimator of rs1970112 (*CDKN2B-AS1*). Genotype allele dosages (0–2) represent the alternative allele count (major C for rs6055069, minor C for rs1970112).

higher polygenic risk scores (mean 0.00846, SD 0.00312) than individuals without CAD (mean 0.00781, SD 0.00319), suggesting that individuals with T1D are modestly affected also by the known CAD susceptibility loci (Supplementary material online, *Figure S4*). Despite a few loci with increased effect sizes in T1D, most of the known CAD risk variants seem to affect those with T1D similarly; effect sizes (β) between the two conditions were correlated ($r = 0.24$, $P = 3.04 \times 10^{-3}$).

3.5 Replication of previous loci

Charmet *et al.*[13] suggested 21 genetic loci within their first-stage GWAS for CAD in T1D. Sixteen of them were studied in our GWAS with no significant associations despite high statistical power for replication (Supplementary material online, *Table S2*). Our GWAS did not replicate the T2D CAD risk SNPs rs10911021 near *GLUL* gene[15] ($P = 0.994$, power = 0.79), rs9299879 within an intron of *MGMT* gene ($P = 0.364$, power = 1.00), or rs57922 close to non-coding RNAs[16] ($P = 0.279$, power = 1.00), nor the CAD risk variant rs74617384 at the *LPA* locus[17] ($P = 0.227$, power = 0.51). However, rs10811652 at 9p21, the lead SNP in the GWAS on CAD in any diabetes,[17] was associated with CAD also in our GWAS ($P = 1.48 \times 10^{-7}$, power = 0.41).

3.6 Gene level and pathway analyses

Mutations increasing CAD risk may accumulate within genes and genetic pathways. Gene scoring supported the *CDKN2B-AS1* association with CAD ($P < 2.5 \times 10^{-6}$, significant after Bonferroni correction). In addition, three genes on chromosome 1 at location 40.94 Mb to 41.01 Mb (*ZFP69*, *EXO5*, and *ZNF684*) reached suggestive significance level, potentially representing the same association signal ($P < 5 \times 10^{-5}$ for each, strongest for *EXO5*; Supplementary material online, *Table S12* and *Figure S5*). The *DEFB125-DEFB127* region was associated with CAD, although not significantly after Bonferroni correction (*P*-values 1.5×10^{-4}, 1.4×10^{-3}, and 1.9×10^{-3}, respectively).

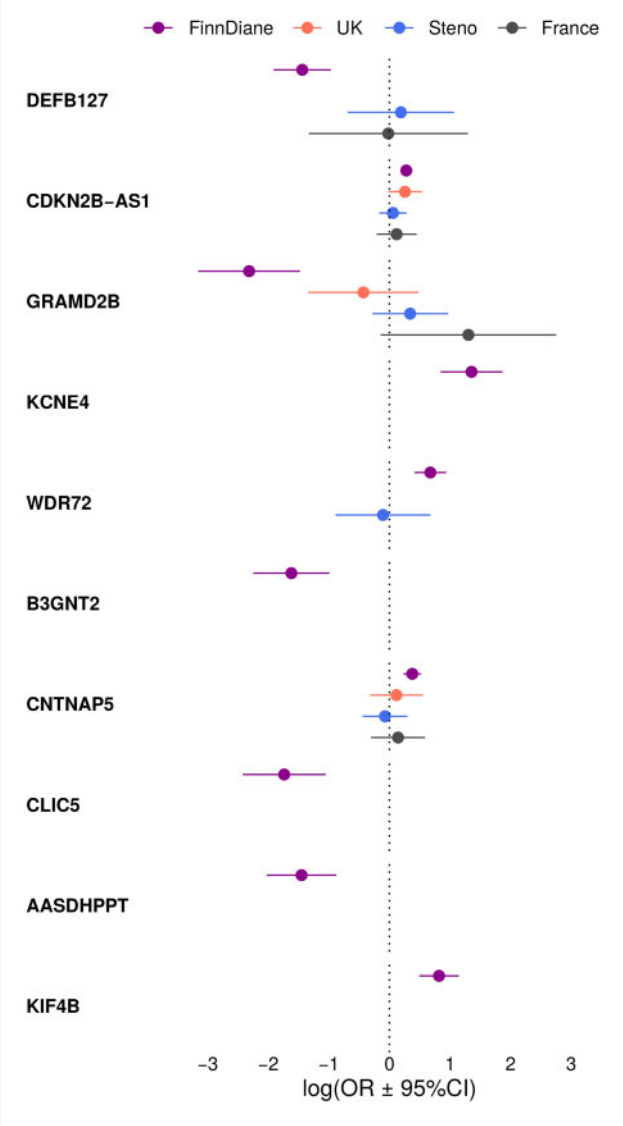


Figure 4 Forest plot of odds ratios in FinnDiane and the replication cohorts. FinnDiane ($N_{cases}/N_{controls}$: 941/3928), France ($N_{cases}/N_{controls}$: 85/1285), Steno ($N_{cases}/N_{controls}$: 237/632), and UK-ROI ($N_{cases}/N_{controls}$: 112/1206).

Pathway scoring revealed only suggestive pathways ($P < 5 \times 10^{-3}$) including recruitment of nuclear mitotic apparatus protein to mitotic centrosomes, and SET pathway (Supplementary material online, *Table S13*).

4. Discussion

GWASs have revealed multiple loci that account for a great proportion of CAD heritability.[10] While diabetes is a well-known risk factor for CAD, and pathophysiology of CAD may differ in T1D from the general population,[5] only a few GWAS have been performed for CAD in individuals with diabetes. We conducted the largest GWAS on CAD in individuals with T1D ($N = 4869$), and identified variants with genome-wide significance in the previously reported 9p21 region within *CDKN2B-AS1*, and on chromosome 20p13 near *DEFB127*. Both loci were also supported by survival analysis from diabetes onset until CAD event.

The 9p21 genetic region has previously been associated with CAD in the general population, as well as with T2D *per se*,[33] and recently also with CAD in individuals with diabetes.[17] However, this is the first time that the locus is associated with CAD in individuals with T1D with genome-wide statistical significance. The effect size was similar for the previously reported lead risk variant at 9p21 in the general population and in T1D. The region includes genes *CDKN2A* and *CDKN2B* encoding for cyclin-dependent kinase inhibitor proteins, which in turn may alter cell proliferation.[34] Similarly to our GWAS, disease risk variants are usually discovered at the non-coding *CDKN2B-AS1* region, which has been suggested to alter histone modifications of other genetic loci by binding to polycomb protein subunits[34] e.g. CBX7 and SUZ12—likely targeting *CDKN2A* and *CDKN2B*, respectively.[35,36] Of note, *CDKN2B-AS1* may act also in trans on *CDKN2B*.[34] Interestingly, Motterle *et al.*[37] showed that genetic variation at 9p21 impact *CDKN2A/B* expression in vascular smooth muscle cells as well as their proliferation rate, thus potentially inducing vascular injury. In our detailed phenotypic analysis, the locus was nominally associated with higher brachial PWV ($P < 0.05$), although not significantly after multiple testing correction ($P < 0.005$). Brachial PWV is indicative of arterial stiffness, which often precedes hypertension and eventually arterial diseases. Lastly, *CDKN2B-AS1* may play a role in inflammatory pathways in co-operation with YY1 transcription factor.[38]

The diabetes-specific discovery at 20p13 locus with $P = 2.35 \times 10^{-9}$ for rs6055069 at the discovery stage, is located only 4 kb upstream of the *DEFB127* gene encoding β-defensin 127 (also known as β-defensin 27). Defensins are small secreted antimicrobial peptides preventing microbial colonization on epithelial surfaces, capable to inhibit the growth of bacteria and fungi. The cationic β-defensins attract negatively charged bacteria, diffuse their hydrophobic part onto the cell membrane of the bacterium and generate pores, eventually leading to cell death. Of note, *DEFB127* has been shown exhibit antimicrobial activity towards *Escherichia coli*.[39] Although *DEFB127* expression is highest at testis and epididymis similarly to many other β-defensins, it is also moderately expressed in the heart, pancreas, kidney, skeletal muscle, liver and lung.[40] Furthermore, β-defensins are believed to contribute to innate and adaptive immune systems.[40] Yang *et al.*[41] suggested that β-defensin 2 chemoattracts memory T-cells and immature dendritic cells, while Soruri *et al.*[42] were unable to replicate this and instead proposed β-defensins 1-4 to chemoattract macrophages. Of note, individuals with diabetes have low grade chronic inflammation,[43] which further contributes to atherosclerosis. However, rs6055069 was not significantly associated with inflammatory markers. Interestingly, individuals with diabetes also have more infections,[44] and thus, *DEFB127* may affect the risk of CAD through elevated infection susceptibility, even though the variant was not directly associated with the yearly amount of antibiotic purchases. Of note, even autoimmunity driven chronic myocardial inflammation has been suggested to play a role in cardiac dysfunction in T1D.[45] We have previously shown that serum α-defensin (Class 1–3) levels are associated with DKD in individuals with T1D,[46] but to our knowledge, this is the first report linking genetic variation in the β-defensin region to cardiovascular outcomes.

Association at the 9p21 locus replicated when adjusted for DKD in 3557 additional individuals with T1D (rs1970112 $P = 0.04$), suggesting DKD independent mechanisms of action. As the association at chromosome 20p13 did not replicate, the signal remains suggestive, pending further confirmation. However, it should be noted that replication data were available only for 322 cases and 1917 controls for the low frequency variant rs6055059, resulting in limited power.

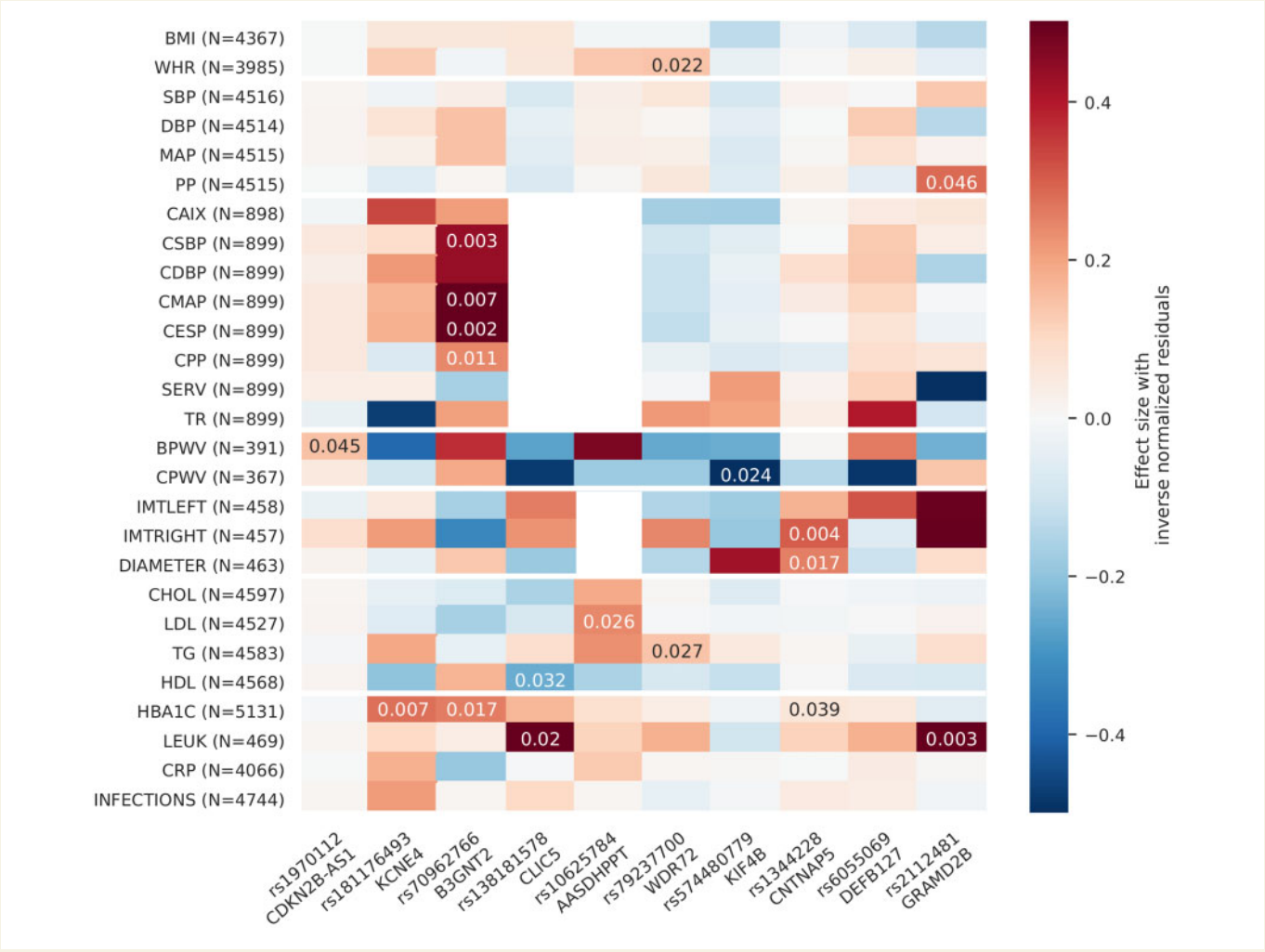


Figure 5 Cardiophenome-wide analysis of variants discovered in GWAS. Coloured according to normalized CAD risk allele effect size and highlighted with significant non-normalized test *P*-values. Association tests were conducted for body mass index (BMI), waist to hip ratio (WHR), systolic blood pressure (SBP), diastolic blood pressure (DBP), mean arterial pressure (MAP), pulse pressure (PP), central augmentation index (CAIX), central systolic blood pressure (CSBP), central diastolic blood pressure (CDBP), central mean arterial pressure (CMAP), central end-systolic pressure (CESP), central pulse pressure (CPP), subendocardial viability ratio (SERV), time to reflection (TR), brachial pulse wave velocity (BPWV), central pulse wave velocity (CPWV), left common carotid artery intima media thickness (IMTLEFT), right common carotid artery intima media thickness (IMTRIGHT), mean common carotid artery diameter (DIAMETER), cholesterol concentration (CHOL), low-density lipoprotein concentration (LDL), log-transformed triglyceride concentration (TG), high-density lipoprotein concentration (HDL), weighted mean HbA1c level (HBA1C), leucocyte concentration (LEUK), log-transformed C-reactive protein concentration (CRP), and log-transformed annual antibiotic purchases (INFECTIONS).

We also discovered eight suggestive genetic variants ($P < 10^{-6}$) in the initial GWAS analysis, albeit with attenuated associations at the meta-analysis stage, if available in replication cohorts. We further attempted to replicate the lead variants from Nikpay *et al.*[29] general population CAD GWAS. Out of the five variants available, including *DEFB127*, only the *CDKN2B-AS1* variant replicated, thus suggesting T1D specific effects.

Three of these suggestive variants showed association with CAD predisposing phenotypes, most importantly rs70962766 (*B3GNT2*) with central blood pressure, rs1344228 (*CNTNAP5*) with atherosclerosis through direct intima-media thickness measures, and rs2112481 (*GRAMD2B*) with leukocyte concentration and therefore inflammation, thus, suggesting potential mechanisms of action. It should be noted that this cardio-phenome-wide analysis for the lead SNPs included a variable number of observations for the studied phenotypes, and only the above-mentioned associations remained significant after correction for ten tested SNPs (but assuming intercorrelation between the CVD-related phenotypes).

PCHiC data in cardiomyocytes suggested chromatin interaction between the lead variant rs2112481 4kbp upstream *GRAMD2B*, and the *GRAMD2B* and *ALDH7A1* genes. Of note, an intronic variant in *ALDH7A1* was recently associated with coronary artery calcified atherosclerotic plaque in a GWAS on African Americans with T2D.[47] Furthermore, gene scoring suggested three genes: *ZFP69*, *EXO5*, and *ZNF684*, of which *ZFP69* has been previously linked to hyperlipidaemia.[48]

Among the known CAD risk variants from the general population, only rs1333049 in *CDKN2B-AS1* was significantly associated with CAD in T1D after correction for multiple testing. Nevertheless, the genetic risk score for the known CAD susceptibility loci was modestly but

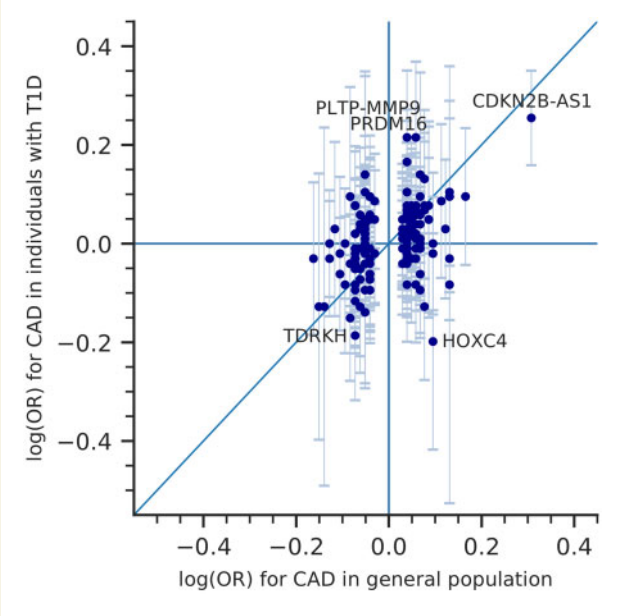


Figure 6 General population CAD risk variant minor allele OR comparison between individuals with and without T1D.

significantly associated with CAD in T1D, suggesting that genetic risk factors discovered in the general population also affect individuals with T1D. Of note, the variant with *PLTP* and *MMP9* as likely target genes showcased a stronger effect size in T1D; *PLTP* has been associated with hypertriglyceridaemia especially in obesity and T2D.[49]

One limitation of the study is the use of registry data. However, the Finnish administrative registers cover all deaths and hospitalization events, and capture CAD events well.[50] In addition, this study suffered from limited power due to moderate GWAS size. However, this is by far the largest GWAS on CAD in individuals with T1D, a group of people with particularly high CAD risk. Furthermore, we have integrated our GWAS with multiple different omics data such as eQTL, left ventricle histone modification, and hESC derived cardiomyocyte chromatin conformation data, linking the SNP associations to interesting target genes.

To conclude, this is the first time that variants on chromosome 9p21 in *CDKN2-AS1* locus were genome-wide significantly associated with CAD in T1D. Furthermore, we identified with genome-wide significance a novel locus for CAD in individuals with T1D on the β-defensin 127 promoter region, potentially acting through infection susceptibility, elevated in individuals with diabetes. While this and the suggestive loci require confirmation in further studies, they suggest novel biological mechanisms for cardiovascular complications in diabetes.

Supplementary material

Supplementary material is available at *Cardiovascular Research* online.

Authors' contributions

A.A.V.A. and N.S. analysed the data, contributed to the interpretation of the data, drafted the work and wrote the manuscript. N.S. further contributed to acquisition of data and conception and study design. A.S. and E.V. contributed to acquisition of genetic data. D.G., C.F., V.H., and P.-H.G. contributed to interpretation of data, acquisition of phenotypic data, and to conception and study design. D.-A.T. contributed to data analysis and interpretation. R.C., A.J.M., and T.S.A. contributed to data analysis. S.H., A.P.M., and P.R. contributed to acquisition of genetic and phenotypic data, to conception and study design. A.S., E.V., D.G., C.F., V.H., P.-H.G., D.-A.T., R.C., A.J.M., T.S.A., S.H., A.P.M., and P.R. revised the work critically for important intellectual content. All authors gave final approval of the version to be published and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Acknowledgements

The authors acknowledge FinnDiane participants and the doctors and nurses participating in the FinnDiane study (Supplementary material online, *Table S13*) and thank the laboratory staff for their skillful work. The authors acknowledge all participants and participating centres from replication cohorts (Supplementary material online, *List of participating centres from French cohorts*). Data on CAD in general population have been contributed by CARDIoGRAMplusC4D investigators and have been downloaded from www.CARDIOGRAMPLUSC4D.ORG. The GTEx project was supported by the Common Fund of the Office of the Director of the National Institutes of Health, and by NCI, NHGRI, NHLBI, NIDA, NIMH, and NINDS. The data reported here were obtained from the GTEx Portal on 07/01/2019 from https://gtexportal.org/home/.

Conflict of interest: P.-H.G. has received investigator-initiated research grants from Eli Lilly and Roche, is an advisory board member for AbbVie, Astellas AstraZeneca, Boehringer Ingelheim, Cebix, Eli Lilly, Janssen, Medscape, Merck Sharp & Dohme, Nestle Novartis, Novo Nordisk, and Sanofi and has received lecture fees from AstraZeneca, Boehringer Ingelheim, Eli Lilly, Elo Water, Genzyme, Merck Sharp & Dohme, Medscape, Mundipharma Novo Nordisk, PeerVoice, Sanofi, and SCIARC. S.H. personally or collectively received research grants, honoraria and fees from the following companies in the last 3 years: Astra Zeneca, Bayer, Boehringer Ingelheim, Dinno Santé, Eli Lilly, LVL, Johnson & Johnson, Medtronic, MSD, NovoNordisk, Novartis, Pierre Fabre Santé, Sanofi, Servier, and Valbiotis. Each disclosed relationship is considered modest, and all other authors declare no conflict of interest.

Funding

This work and the FinnDiane project were supported by the Folkhälsan Research Foundation, Wilhelm och Else Stockmann Foundation, Novo Nordisk Foundation [NNFOC0013659], Liv och Hälsa Society, Helsinki University Central Hospital Research Funds (EVO) and Academy of Finland [299200, 275614, and 316664], European Foundation for the Study of Diabetes (EFSD) Young Investigator Research Award funds [to N.S.], Ida Montini Foundation [to A.A.V.A.], an EFSD award supported by EFSD/Sanofi European Diabetes Research Programme in Macrovascular Complications, and Finnish Foundation for Cardiovascular Research. Genotyping of the GWAS data for discovery and replication cohorts was funded by the Juvenile Diabetes Research Foundation (JDRF) within the Diabetic Nephropathy Collaborative Research Initiative [DNCRI; 17-2013-7], with GWAS quality control and imputation performed at University of Virginia. R.C. was financially supported by a PhD grant from the Region Ile de France (CORDDIM). Recruitment of the UK-ROI cohort was funded by Diabetes UK and the JDRF. Further research involving the UK-ROI cohort was funded by grants

from Health Research Board, Science Foundation Ireland, Northern Ireland Public Health Agency (Research & Development Division) and Medical Research Council as part of the USA-Ireland-Northern Ireland research partnership and Department for the Economy NI 15/IA/3152; this funding supported investigators in the Warren 3/UK GoKinD Study Group, which includes, Belfast: A.P. Maxwell, A.J. McKnight, D.A. Savage; Edinburgh: J. Walker; London: S. Thomas, G.C. Viberti; Manchester: A.J. M. Boulton; Newcastle: S. Marshall; Plymouth: A.G. Demaine, B.A. Millward; Swansea: S.C. Bain.

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Translational perspective

Genetic association studies enable the discovery of novel genes and genetic pathways associated with the disease. Thus, this study provides an insight into coronary artery disease mechanisms specific to type 1 diabetes. The *DEFB127* discovery may lead to a therapeutic target and improve patient care, if replicated in the future. Furthermore, genetic studies on coronary artery disease in type 1 diabetes are required for accurate personalized treatment plans achieved through genetic data for those with type 1 diabetes.