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Genome-wide meta-analysis identifies five new susceptibility loci for pancreatic cancer

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In 2020, 146,063 deaths due to pancreatic cancer are estimated to occur in Europe and the United States combined. To identify common susceptibility alleles, we performed the largest pancreatic cancer GWAS to date, including 9040 patients and 12,496 controls of European ancestry from the Pancreatic Cancer Cohort Consortium (PanScan) and the Pancreatic Cancer Case-Control Consortium (PanC4). Here, we find significant evidence of a novel association at rs78417682 (7p12/*TNS3*, $P = 4.35 \times 10^{-8}$). Replication of 10 promising signals in up to 2737 patients and 4752 controls from the PANcreatic Disease ReseArch (PAN-DoRA) consortium yields new genome-wide significant loci: rs13303010 at 1p36.33 (*NOC2L*, $P = 8.36 \times 10^{-14}$), rs2941471 at 8q21.11 (*HNF4G*, $P = 6.60 \times 10^{-10}$), rs4795218 at 17q12 (*HNF1B*, $P = 1.32 \times 10^{-8}$), and rs1517037 at 18q21.32 (*GRP*, $P = 3.28 \times 10^{-8}$). rs78417682 is not statistically significantly associated with pancreatic cancer in PANDoRA. Expression quantitative trait locus analysis in three independent pancreatic data sets provides molecular support of *NOC2L* as a pancreatic cancer susceptibility gene.

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Pancreatic cancer is currently the third leading cause of cancer-related deaths in the United States and the fifth leading cause in Europe^{1,2}, and is predicted to become the second leading cause of cancer-related deaths in the United States by 2030^{3,4}. Incidence rates of pancreatic cancer have also gradually increased¹. Genetic susceptibility plays an important role in pancreatic cancer risk through mutations in known genes for hereditary cancer or hereditary pancreatitis^{5–11}, and common genetic variants identified through genome-wide association studies (GWAS)^{12–16}.

With the aim of identifying additional common pancreatic cancer risk loci, the Pancreatic Cancer Cohort Consortium (PanScan: <https://epi.grants.cancer.gov/PanScan/>) and the Pancreatic Cancer Case-Control Consortium (PanC4: <http://www.panc4.org/>) have performed GWAS of pancreatic ductal adenocarcinoma (PDAC) in populations of European ancestry. These studies, namely PanScan I¹², PanScan II¹³, PanScan III^{14,15}, and PanC4¹⁶, have led to the identification of 13 genomic loci carrying 17 independent pancreatic cancer risk signals on chromosomes 1q32.1 (two independent signals in *NR5A2*), 2p14 (*ETAA1*), 3q28 (*TP63*), 5p15.33 (three independent risk loci in the *CLPTMIL-TERT* gene region), 7p14.1 (*SUGCT*), 7q23.2 (*LINC-PINT*), 8q24.1 (two independent risk loci in the *MYC-PVT1* gene region), 9q34.2 (*ABO*), 13q12.2 (*PDX1*), 13q22.1 (non-genic), 16q23.1 (*BCAR1*), 17q24.3 (*LINC00673*), and 22q12.1 (*ZNRF3*)^{12–16}. A fourth independent risk locus at 5p15.33 (*TERT*) was identified through a candidate gene analysis by the PANcreatic Disease ReseArch (PANDoRA) case-control consortium^{17,18}. GWAS in populations from China¹⁹ and Japan²⁰ have identified eight additional GWAS significant pancreatic cancer risk loci on chromosomes 5p13.1 (*DAB2*), 6p25.3 (*FOXQ1*), 7q36.2 (*DPP6*), 12p11.21 (*BICD1*), 10q26.11 (*PRLHR*), 21q21.3 (*BACH1*), 21q22.3 (*TFF1*), and 22q13.32 (*FAM19A5*)¹⁹. The overlap among loci identified in the European and Asian ancestry scans with current sample sizes is limited^{14,16,21}.

Here we report the findings of the largest Pancreatic Cancer GWAS study to date. Five novel regions of association were identified. A locus at rs78417682 (7p12/*TNS3*, $P = 4.35 \times 10^{-8}$) was identified in meta-analysis of the PanScan I/II, PanScan III, and PanC4 data. Four additional loci, rs13303010 at 1p36.33 (*NOC2L*, $P = 8.36 \times 10^{-14}$), rs2941471 at 8q21.11 (*HNF4G*, $P = 6.60 \times 10^{-10}$), rs4795218 at 17q12 (*HNF1B*, $P = 1.32 \times 10^{-8}$), and rs1517037 at 18q21.32 (*GRP*, $P = 3.28 \times 10^{-8}$) were identified after replication in additional cases and controls from the PANDoRA consortium.

Results

Association analysis. In the current study, we performed the largest association analysis of pancreatic cancer risk to date, including 9040 individuals diagnosed with pancreatic cancer and 12,496 control individuals of European ancestry (Supplementary Table 1) from four GWAS studies (PanScan I, PanScan II, PanScan III, and PanC4). These individuals were previously genotyped on the Illumina HumanHap550, 610-Quad, OmniExpress, and OmiExpressExome arrays, respectively^{12–16}. Because of the extensive overlap of variants on the arrays, data from PanScan I and PanScan II were analyzed jointly, while PanScan III and PanC4 were each analyzed separately. Imputation was performed using the 1000 G (Phase 3, v1) reference data set²². After quality control 11,381,182 variants were analyzed for 21,536 individuals (7167 in PanScan I+II, 6785 in PanScan III, and 7584 in PanC4). A quantile–quantile plot (Supplementary Figure 1) showed little evidence of systematic inflation ($\lambda = 1.002$ for PanScan I+II, $\lambda = 1.051$ for PanScan III, $\lambda = 1.025$ for PanC4, and $\lambda = 1.05$ for the meta-analysis).

In a fixed-effect meta-analysis of PanScan I+II, PanScan III, and PanC4, we observed robust associations at our previously identified susceptibility loci in individuals of European ancestry^{12–16} (Supplementary Table 2). We also noted one novel locus that met the genome-wide significance threshold ($P < 5 \times 10^{-8}$: Wald test) at chromosome 7p12 in the *TNS3* gene, and nine additional promising loci ($P < 1 \times 10^{-6}$: Wald test). These 10 loci were carried forward to an independent replication in up to 2737 pancreatic cancer cases and 4752 control individuals from the PANcreatic Disease ReseArch (PANDoRA) consortium²³. In a combined meta-analysis of up to 11,537 pancreatic cancer cases and 17,107 control individuals from PanScan I+II, PanScan III, PanC4, and PANDoRA, we identified three additional loci of genome-wide significance: rs13303010 at 1p36.33 (*NOC2L*, odds ratio (OR) = 1.26; 95% confidence interval (CI) 1.19–1.35, $P = 8.36 \times 10^{-14}$: Wald test), rs2941471 at 8q21.11 (*HNF4G*, OR = 0.89, 95% CI 0.85–0.93, $P = 6.60 \times 10^{-10}$: Wald test), and rs4795218 at 17q12 (*HNF1B*, OR = 0.88, 95% CI 0.84–0.92, $P = 1.32 \times 10^{-8}$: Wald test). A locus that was previously reported to be suggestive in the PanC4 study at 18q21.32 in the *GRP* gene¹⁶ also surpassed the significance threshold (rs1517037, OR = 0.86, 95% CI 0.80–0.91, $P = 3.28 \times 10^{-8}$: Wald test) in our meta-analysis. (Table 1 and Fig. 1). The single-nucleotide polymorphism (SNP) at 7p12 in *TNS3* (rs73328514) was not significantly associated with pancreatic cancer in PANDoRA (OR = 0.94, $P_{\text{PANDoRA}} = 0.31$; OR = 0.85, $P_{\text{Combined}} = 1.35 \times 10^{-7}$: Wald test).

The marker SNP at 1p36.33 (rs13303010) maps to the first intron of the *NOC2L* gene, which encodes the nucleolar complex protein 2 homolog (NOC2-like protein, also known as novel INHAT repressor), an inhibitor of histone acetyltransferase (HAT) activity and transcriptional repressor²⁴. This protein also directly binds to p53, stabilizing an interaction between the mitotic kinase Aurora B and p53, resulting in inhibition of p53-mediated transcriptional activation^{24,25}. Likewise, NOC2-like protein binds and inhibits transcriptional activity of the closely related tumor suppressor protein, p63 (TAp63)²⁶. Notably, we have previously identified a pancreatic cancer risk locus intronic to the *TP63* gene¹⁶.

At chromosome 8q21.11, the newly associated SNP (rs2941471) is intronic to *HNF4G*, which encodes hepatocyte nuclear factor 4 gamma, a transcription factor (TF) of the nuclear receptor superfamily. Mice lacking *Hnf4g* have higher numbers of pancreatic β -cells, increased glucose-induced insulin secretion, and improved glucose tolerance²⁷. Of the multiple GWAS that have reported association signals at this locus for other conditions, the variant with the highest linkage disequilibrium (LD) with our pancreatic cancer-associated variant, rs2941471, has been significantly associated with variations in serum urate concentrations (rs2941484²⁸, $r^2 = 0.56$, in 1000 G EUR). Interestingly, we have previously shown that urate levels are associated with pancreatic cancer risk²⁹. Additional variants in the *HNF4G* gene region, including those significantly associated with body mass index (BMI)³⁰, obesity³¹, and breast cancer³² are less correlated with rs2941471 ($r^2 = 0.02$ – 0.12).

The signal at 17q12 (rs4795218) maps to the fourth intron of *HNF1B*, encoding another member of the hepatocyte nuclear factor family. *HNF1B* plays an important role in pancreatic development, acting in a transcriptional network that controls the differentiation of multipotent progenitor cells to acinar, ductal, and endocrine cells^{33,34}. Mutations in *HNF1B* account for a small percentage (1–2%) of maturity onset diabetes of the young (MODY)³⁵. In addition, variants in the *HNF1B* gene region that are modestly linked with rs4795218 have previously been associated with the development of prostate cancer (rs4794758, $r^2 = 0.59$ in 1000 G EUR)³⁶. Although additional variants in this

Table 1 Novel pancreatic cancer susceptibility loci

Chr ^a SNP Position ^b gene	Effect allele (minor)/reference allele	Statistic	PanScan I/II 3535 cases and 3642 controls	PanScan III 1582 cases and 5203 controls	PanC4 3933 cases and 3651 controls	ALL GWAS 9040 cases and 12,496 controls	PANDoRA 2497 cases and 4611 controls	GWAS +PANDoRa 11,537 cases and 17,107 controls
1p36.33 rs13303010 894,573 NOC2L	G/A	MAF ^c cases; controls	0.14; 0.13	0.12; 0.10	0.13; 0.11		0.14; 0.10	-
		Info ^d	0.42	g	g		g	-
		OR (CI)	1.15 (1.01-1.26)	1.22 (1.09-1.33)	1.16 (1.07-1.24)	1.20 (1.12-1.29)	1.45 (1.33-1.57)	1.26 (1.19-1.35)
		P value	3.64 × 10 ⁻²	1.48 × 10 ⁻³	9.54 × 10 ⁻⁴	7.30 × 10 ⁻⁷	6.00 × 10 ⁻¹⁰	8.36 × 10 ⁻¹⁴
		Heterogeneity P value ^e					6.49 × 10 ⁻¹	4.57 × 10 ⁻²
7p12 rs73,328,514 47488569 TNS3	T/A	MAF cases; controls	0.09; 0.11	0.10; 0.12	0.10; 0.12		0.10; 0.11	-
		Info	0.93	0.97	0.97		g	-
		OR (CI)	0.80 (0.71-0.89)	0.88 (0.76-1.02)	0.82 (0.74-0.92)	0.83 (0.77-0.88)	0.94 (0.83-1.06)	0.85 (0.80-0.90)
		P value	8.38 × 10 ⁻⁵	9.31 × 10 ⁻²	3.61 × 10 ⁻⁴	4.35 × 10 ⁻⁸	3.08 × 10 ⁻¹	1.35 × 10 ⁻⁷
		Heterogeneity P value					5.98 × 10 ⁻¹	2.35 × 10 ⁻¹
8q21.11 rs2941471 76,470,404 HNF4G	G/A	MAF cases; controls	0.40; 0.43	0.41; 0.42	0.41; 0.43		0.40; 0.43	
		Info	1.0	1.0	1.0		g	
		OR (CI)	0.87 (0.79-0.94)	0.91 (0.80-1.01)	0.89 (0.82-0.96)	0.89 (0.86-0.94)	0.87 (0.79-0.94)	0.89 (0.85-0.93)
		P value	2.39 × 10 ⁻⁴	8.30 × 10 ⁻²	2.19 × 10 ⁻³	4.73 × 10 ⁻⁷	2.42 × 10 ⁻⁴	6.60 × 10 ⁻¹⁰
		Heterogeneity P value					7.73 × 10 ⁻¹	7.87 × 10 ⁻¹
17q12 rs4795218 36,078,510 HNF1B	A/G	MAF cases; controls	0.20; 0.23	0.22; 0.23	0.21; 0.23		0.21; 0.23	
		Info	0.96	0.96	0.95		g	
		OR (CI)	0.87 (0.80-0.95)	0.88 (0.78-0.98)	0.88 (0.81-0.95)	0.88 (0.82-0.93)	0.90 (0.82-0.98)	0.88 (0.84-0.92)
		P value	1.12 × 10 ⁻³	2.29 × 10 ⁻²	1.11 × 10 ⁻³	2.73 × 10 ⁻⁷	1.38 × 10 ⁻²	1.32 × 10 ⁻⁸
		Heterogeneity P value					9.96 × 10 ⁻¹	9.78 × 10 ⁻¹
18q21.32 rs1517037 56,878,274 GRP	T/C	MAF cases; controls	0.16; 0.19	0.17; 0.19	0.17; 0.18		0.17; 0.19	
		Info	g	g	g		g	-
		OR (CI)	0.82 (0.75-0.89)	0.92 (0.82-1.04)	0.90 (0.83-0.98)	0.87 (0.82-0.93)	0.87 (0.79-0.97)	0.86 (0.80-0.91)
		P value	7.56 × 10 ⁻⁶	1.90 × 10 ⁻¹	1.64 × 10 ⁻²	8.81 × 10 ⁻⁷	1.17 × 10 ⁻²	3.28 × 10 ⁻⁸
		Heterogeneity P value					1.87 × 10 ⁻¹	7.73 × 10 ⁻²

^a Cytogenetic regions according to NCBI Human Genome Build 37

^b SNP position according to NCBI Human Genome Build 37

^c Minor allele frequency

^d Quality of imputation metric. See online methods for more detail. If a SNP is genotyped and not imputed, a "g" is reported

^e P value from test of heterogeneity

region have been associated with other cancers including prostate³⁶, endometrial³⁷, and testicular³⁸ cancers, they do not appear to mark the same signal (rs4430796, rs11263763, rs7501939, respectively, r^2 with rs4795218 \leq 0.005 in 1000 G EUR).

The two novel risk loci in genes of the hepatocyte nuclear factor family are intriguing in light of our previously published suggestive evidence of association with other members of this family, including a locus at 12q24.31 in the *HNF1A* gene (rs1182933, OR = 1.11, $P = 3.49 \times 10^{-7}$; Wald test) and a locus on 20q13.11 ~20 kb downstream of the *HNF4A* gene (rs6073450, OR = 1.09, $P = 4.55 \times 10^{-6}$; Wald test; Supplementary Table 3)¹⁶. Members of this family of TFs play important roles in pancreatic development and regulate specific gene expression programs in pancreatic acini, pancreatic islets, and hepatocytes in adults³⁹⁻⁴². Importantly, *HNF1A* appears to be a critical member of a signaling network that maintains homeostasis in the adult

pancreas^{40,43}. We have also previously shown that *HNF1A* may be a tumor suppressor gene in the pancreas^{44,45}. Inherited mutations in several genes of this family cause pancreatic beta cell dysfunction resulting in MODY: *HNF4A* (MODY 1), *HNF1A* (MODY 3), and *HNF1B* (MODY 5)³⁵. Common variants in or close to some of these genes have also been significantly associated with type 2 diabetes (T2D) and body mass index (BMI)/obesity, both known epidemiologic risk factors for pancreatic cancer⁴⁶. However, the low LD between those signals on 8q21.11/*HNF4G* (PDAC-rs2941471 and BMI-rs17405819⁴⁷, $r^2 = 0.05$), 17q12/*HNF1B* (PDAC-rs4795218 and T2D-rs4430796⁴⁸, $r^2 = 0.0007$), and 12q24.31/*HNF1A* (PDAC-rs7310409 and T2D-rs12427353⁴⁸, $r^2 = 0.18$) indicates that the underlying functional mechanism for the pancreatic cancer GWAS signals may differ from those for adult-onset T2D and BMI.

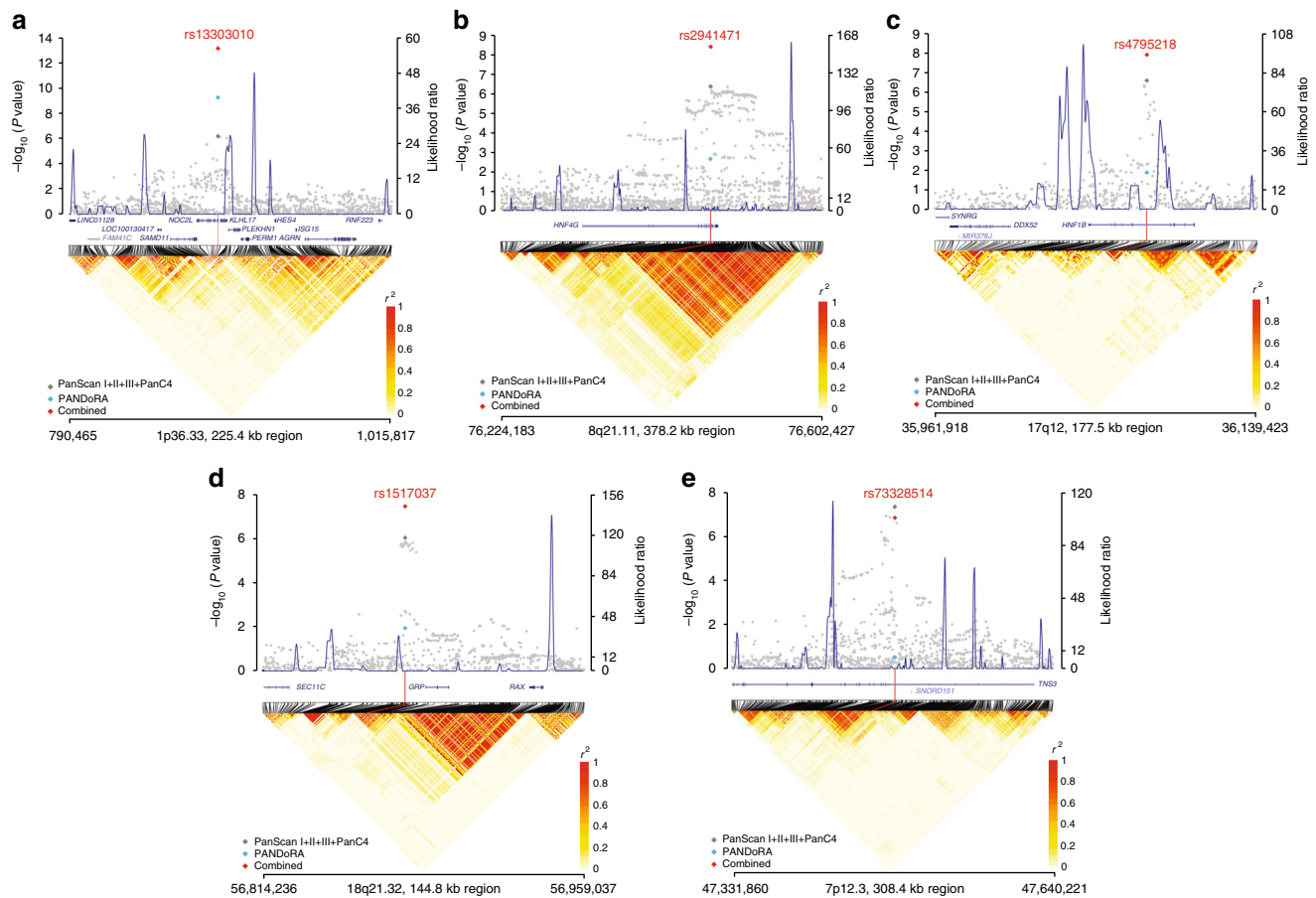


Fig. 1 Association results, recombination hotspots, and LD plots for new pancreatic cancer susceptibility regions. The top half of each panel shows the association results for the meta-analysis of PanScan I+II, PanScan III, and PanC4 (gray diamonds). The results for the replication of the marker SNP at each locus are shown for PANDoRA (light blue diamonds) and the combined meta-analysis results (red diamonds). Overlaid are likelihood ratio statistics estimating putative recombination hotspots across the region based on the inference using the CEU 1000 G Phase 3 data. Genomic coordinates are plotted on the x axis (Genome build hg19), P values for the association analysis are shown on the left y axis, and recombination hotspot likelihood ratio on the right y axis. The bottom half of each panel shows LD heat maps based on r^2 values from the 1000 G Phase 3 CEU population for all variants included in the analysis. Shown are results for chromosomes 1p36.33 (**a**), 8q21.11 (**b**), 17q12 (**c**), 18q21.32 (**d**), and 7p12 (**e**)

At 18q21.32, the signal marked by rs1517037 is ~10 kb upstream of the *GRP* gene, which encodes a member of the bombesin-like family of gastrin-releasing peptides that stimulates the release of gastrointestinal hormones, including amylase⁴⁹, a marker of acute pancreatitis. Correlated variants at this locus ($r^2 = 0.82$ –1.00) are associated with inflammatory bowel disease (IBD)⁵⁰ and BMI⁴⁷.

The locus at 7p12 is marked by an intronic SNP (rs73328514) in *TNS3*. This gene encodes Tensin-3, a member of a family of focal adhesion-associated proteins (Tensin-1 through Tensin-4) that regulate cell adhesion and migration⁵¹ and may play a role in metastasis⁵².

We identified suggestive evidence for additional risk loci in the meta-analysis of PanScan and PanC4 data; at 9q31.1 in the *SMC2* gene (rs2417487, $P = 1.49 \times 10^{-7}$: Wald test), at 4q31.22 near *EDNRA* (rs6537481, $P = 1.15 \times 10^{-7}$: Wald test), and at 16q24.1 near *LINC01081/LINC00917* (rs7200646, $P = 1.39 \times 10^{-7}$: Wald test) but these were not significantly associated in PANDoRA ($P = 0.38, 0.91$ and 0.93 , respectively: Wald tests; Supplementary Table 4). *SMC2* encodes a subunit of condensin and is necessary for chromosome organization, cell division, and DNA repair⁵³. *EDNRA* encodes the endothelin-1 receptor and has been associated with pancreatic cancer prognosis⁵⁴. The locus on 16q24.1 lies ~200–300 kb upstream of a cluster of genes of the forkhead family of TFs (*FOXF1*, *FOXC2*, and *FOXL1*), known for

their roles in development, cell proliferation, and several diseases, including cancer⁵⁵.

We further estimated a polygenic risk score (PRS) for pancreatic cancer using the 22 independent genome-wide significant risk SNPs in the Caucasian population^{12–16}. The OR for pancreatic cancer among individuals above the 90th percentile the risk distribution was 2.20 (95% CI 1.83–2.65) compared with those with a PRS in the 40–60th percentile (Supplementary Table 5). We also assessed eight pancreatic cancer risk loci identified in Chinese and Japanese individuals in our data and noted one nominally significant locus in the combined PanScan and PanC4 results (6p25.3, rs9502893, OR = 0.94, 95% CI 0.92–0.97, $P = 0.009$: Wald test; Supplementary Table 6).

Pathway enrichment analysis. Pathway enrichment analysis for genes in currently known pancreatic cancer risk loci was performed using gene set enrichment analysis (GeneCodis; <http://genecodis.cnb.csic.es/analysis>)⁵⁶ and Data-Driven Expression Prioritized Integration for Complex Traits (DEPICT; <https://data.broadinstitute.org/mpg/depict/>)⁵⁷. The most significant enrichment was seen for the terms “Maturity onset diabetes of the young” (Kyoto Encyclopedia of Genes and Genomes (KEGG), $P = 5.5 \times 10^{-9}$, Hypergeometric distribution test), “Sequence-specific DNA-binding transcription factor activity” (GO Molecular

Table 2 Expression quantitative trait loci (eQTLs) for marker SNPs on chromosomes 1p36.33 and 8q21.11 in histologically normal pancreatic tissue samples from GTEx ($n = 149$) and LTG ($n = 95$) as well as pancreatic tumor samples from TCGA (PDAC, $n = 115$)

Chr1p36.33: eQTLs for rs13303010

Gene name	GTEx pancreas		LTG pancreas		TCGA PDAC	
	P value	Effect size*	P value	Effect size*	P value	Effect size*
<i>KLHL17</i>	2.10×10^{-5}	-0.42	0.131	-0.32	0.654	-0.11
<i>NOC2L</i>	0.001	0.39	0.019	0.41	0.043	0.49
<i>SAMD11</i>	0.023	-0.26	0.500	0.14	0.397	-0.18
<i>DVL1</i>	0.042	-0.14	0.280	0.18	0.085	-0.37

Chr8q21.11: eQTLs for rs2941471

Gene name	GTEx pancreas		LTG pancreas		TCGA PDAC	
	P value	Effect size*	P value	Effect size*	P value	Effect size*
<i>HNF4G</i>	0.038	0.15	0.024	0.28	0.803	-0.029

Expression QTLs were assessed in GTEx pancreatic tissue samples for all RefSeq genes within a 1 MB region centered on the marker SNP at each locus. Nominally significant findings were attempted for replication in the LTG and TCGA pancreatic tissue samples. *Effect size is the estimated eQTL effect size or beta (β) and its direction is shown for the risk increasing allele at each locus

Function, $P = 3.1 \times 10^{-4}$), “Cellular response to UV” (GO Biological Process, $P = 4.2 \times 10^{-4}$, Hypergeometric distribution test) as well as multiple gastrointestinal tissues (DEPICT, $P = 5.1 \times 10^{-5}$ –0.004, Welch’s t -test; Supplementary Tables 7 and 8).

Expression analysis. To begin unraveling the functional consequences of the newly discovered risk alleles, we performed expression quantitative trait locus (eQTL) analyses in three independent pancreatic tissue sample sets. We first assessed eQTLs in the publicly available Genotype-Tissue Expression (GTEx) project data for 149 histologically normal pancreatic tissue samples (including genes in a 1MB window centered on the marker SNP at each locus). Nominally significant eQTLs ($P < 0.05$) from this analysis (Supplementary Table 9, Supplementary Figure 2) were then carried forward to replication in two additional sample sets: (1) 95 histologically normal pancreatic samples (Laboratory of Translational Genomics, Laboratory of Translational Genomics (LTG) set⁵⁸) and (2) 115 pancreatic tumors (The Cancer Genome Atlas, TCGA, Pancreatic Adenocarcinoma, PAAD, samples⁵⁸; Table 2). The most notable eQTL in this analysis was seen for 1p36.33, where the risk-increasing allele at rs13303010 was associated with higher *NOC2L* expression in all three data sets (GTEx: $P = 0.01$, $\beta = 0.39$; LTG: $P = 0.019$, $\beta = 0.41$; TCGA: $P = 0.043$, $\beta = 0.49$; T-statistic; Fig. 2b). An additional eQTL for a nearby gene, *KLHL17*, was significant in GTEx ($P = 2.1 \times 10^{-5}$, $\beta = -0.42$; T-statistic) but not in LTG ($P = 0.131$, $\beta = -0.32$; T-statistic) or TCGA ($P = 0.654$, $\beta = -0.11$; T-statistic). At 8q21.11, the risk allele (rs2941471-A) was associated with higher expression of *HNF4G* in GTEx ($P = 0.038$, $\beta = 0.15$; T-statistic) and LTG ($P = 0.024$, $\beta = 0.28$; T-statistic) samples, but not in TCGA ($P = 0.80$, $\beta = -0.029$; T-statistic).

At 1p36.33/*NOC2L*, we analyzed the set of variants most likely to be functional ($LR > 1:100$, $n = 10$) for overlap with transcriptionally active chromatin and effects on predicted TF-binding sites. The most notable variant in this analysis was rs13303160 ($r^2 = 0.93$ with rs13303010) that overlaps open chromatin and prominent histone modification marks in ENCODE data (Fig. 2a,

Supplementary Table 10) and where the risk allele is predicted to strongly disrupt TF-binding motifs for SMARCC1 (also known as BAF155) and several AP-1 proteins (Fig. 2c, Supplementary Table 11). These analyses suggest that altered SMARCC1 or AP-1 binding at rs13303160 may lead to higher levels of *NOC2L* mRNA. An increase in *NOC2L* protein would be expected to result in lower levels of histone acetylation and repression of p53 and p63 transcriptional activity^{24–26,59}. We also assessed differential expression of *NOC2L* (and additional genes at the five novel loci) in pancreatic tumors⁴⁴ and noted a 3.98-fold ($P = 9.69 \times 10^{-10}$; EdgeR, Exact test) increased expression in pancreatic cancer cell lines ($n = 9$) as compared with histologically normal pancreatic tissue samples ($n = 10$; Supplementary Table 12).

Discussion

This study demonstrates the power of large-scale collaborations in identifying new risk loci for pancreatic cancer, a deadly disease that presents challenges in accruing large sample sets for genetic studies. We herein add to the number of pancreatic cancer risk loci in or close to genes involved in MODY. As these genes also play roles in pancreatic development and acinar homeostasis, they may help explain underlying mechanisms at these loci. However, due to the low LD with BMI and T2D GWAS variants, the underlying mechanisms may differ between these epidemiologically and pathophysiologically associated conditions. We also describe potential functional underpinnings of risk loci, in particular for the locus on chromosome 1p36.33 in *NOC2L*, that require further detailed investigation.

Methods

Study participants. Participants were drawn from the Pancreatic Cancer Cohort Consortium (PanScan) and the Pancreatic Cancer Case-Control Consortium (PanC4) and individuals were included from 16 cohort and 13 case-control studies genotyped in four previous GWAS phases, namely PanScan I, PanScan II, PanScan III, and PanC4^{12–14,16}. Samples from the PANDoRA case-control consortium were used for replication²³. The details on cases (individuals with PDAC) and controls have been previously described^{12–14,16}.

All studies obtained informed consent from study participants and Institutional Review Board (IRB) approvals including IRB certifications permitting data sharing in accordance with the NIH Policy for Sharing of Data Obtained in NIH Supported or Conducted GWAS. The PanScan and PanC4 GWAS data are available through dbGAP (accession numbers phs000206.v5.p3 and phs000648.v1.p1, respectively).

Genotyping, imputation, and association analysis. Genotyping for PanScan was performed at the Cancer Genomics Research Laboratory (CGR) of the National Cancer Institute (NCI) of the National Institutes of Health (NIH) using the Illumina HumanHap series arrays (Illumina HumanHap550 Infinium II, Human 610-Quad) for PanScan I and II, respectively, and the Illumina Omni series arrays (OmniExpress, Omni1M, Omni2.5, and Omni5M) for PanScan III^{12–14}. Genotyping for the PanC4 GWAS was performed at the Johns Hopkins Center for Inherited Disease Research (CIDR) using the Illumina HumanOmniExpressExome-8v1 array. Imputation was performed using the 1000 Genomes (1000G) Phase 3, Release 1 reference data set²² and IMPUTE2 (http://mathgen.stats.ox.ac.uk/impute/impute_v2.html)⁶⁰ as previously described^{14,18}. Because of the large overlap of variants on genotyping arrays for PanScan I and II, these data sets were imputed and analyzed together. The PanScan III and PanC4 GWAS data sets were each imputed and analyzed separately. For quality control, variants were excluded based on (1) completion rate $< 90\%$; (2) MAF < 0.01 ; and (3) low-quality imputation score (IMPUTE2 INFO score < 0.3). After quality control, 11,381,182 SNPs genotyped or imputed in 5107 pancreatic cancer patients and 8845 controls of European ancestry were included in the analysis for PanScan I-III and 3933 cases and 3651 controls for PanC4 (Supplementary Table 1). The association analysis was performed using SNPTEST (http://mathgen.stats.ox.ac.uk/genetics_software/snpstest/snpstest.html)⁶¹ based on probabilistic genotype values from IMPUTE2⁶⁰, with parallel covariate adjustments: study, geographical region, age, sex, and principal components (PCA) of population substructure as were used in PanScan^{12–14} and study, age, sex, and PCA population substructure as were used in PanC4¹⁶. The score statistic of the log additive genetic association magnitude was used. Summary statistics from PanScan I and II, PanScan III, and PanC4 were used for a meta-analysis using the fixed-effects inverse-variance method based on β estimates and SEs (<http://csg.sph.umich.edu/abecasis/metal/>). Heterogeneity was not observed for the SNPs identified as GWAS significant or suggestive in the combined study ($P_{\text{heterogeneity}} \geq 0.32$). IMPUTE2 information scores were above 90% for SNPs ($P < 1 \times 10^{-6}$), except for rs13303010 in the PanScan I+II data (INFO = 0.42;

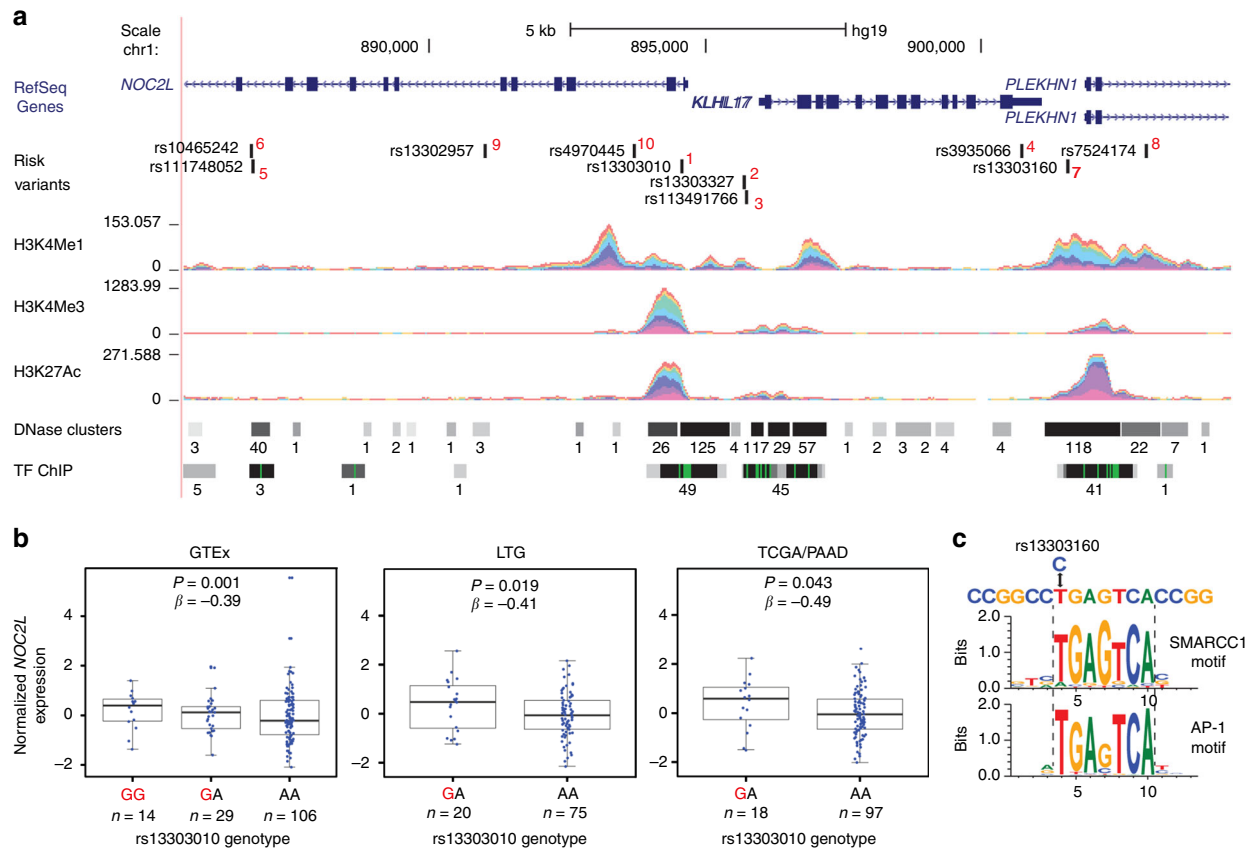


Fig. 2 Functional analysis of the 1p36.33 risk locus. **a** The set of most likely functional variants at 1p36.33 and their P value rank (1–10, in red) is shown as well as overlapping RefSeq genes on chr1: 885,555–904,522 (NCBI GRCh37/Hg19). ENCODE data for histone modification marks (H3K4me1, H3K4me3, H3K27Ac) are indicated by colored density plots. Open chromatin (DNase hypersensitivity regions, DNase clusters) and binding of transcription factors (TF ChIP) are indicated by horizontal bars. The numbers next to each bar indicate the number of cell lines with DNase clusters, or the number of different transcription factors bound across all tested cell lines. The panel is adapted from the UCSC Genome Browser. **b** Expression QTLs in histologically normal autopsy-derived pancreatic tissues ($n = 149$) from the GTEx consortium (GTEx), the Laboratory of Translational Genomics histologically normal adjacent-to-tumor pancreatic tissue set (LTG, $n = 95$), and the TCGA pancreatic cancer tissue set (TCGA/PAAD, $n = 115$). Normalized *NOC2L* expression is shown on the y axis and genotypes at the marker SNP at 1p36.33 on the x axis. Risk-increasing alleles are marked in red. Note that no samples in the LTG and TCGA/PAAD sets were of the minor homozygous risk genotype (GG). The box-and-whisker plots show the median (horizontal middle line within each box), interquartile range (top and bottom horizontal lines of each box), and 1.5 times the IQR (whiskers). **c** Analysis of the effects of 1p36.33 variants on transcription factor motifs for rs13303160 ($r^2 = 0.93$ with rs13303010 in 1000 G EUR). The risk allele (C) at this marker alters predicted DNA-binding motifs for SMARCC1 and AP-1 proteins

Table 1). The estimated inflation of the test statistic, λ , was 1.002 for PanScan I+II, 1.051 for PanScan III, and 1.024 for PanC4⁶².

A Polygenic Risk Score (PRS) was constructed for each individual by summing the number of risk alleles carried for all established pancreatic cancer risk loci identified by GWAS, weighted by their estimated effect size. Individuals were grouped by percentiles, and the association of the PRS (as percentile groupings) with pancreatic cancer was estimated using logistic regression.

DEPICT analysis was used to prioritize causal genes at currently known pancreatic cancer risk loci^{12–16} identify gene sets enriched across risk loci, and tissues in which genes at risk loci are highly expressed⁵⁷. No genes or SNP–gene pairs were significant at false discovery rate (FDR) < 0.05 (data not shown) but significant tissue enrichment is shown in Supplementary Table 7. Additional gene set enrichment analysis was performed using GeneCodis3 (<http://genecodis.cnb.csic.es/>). Genes ($n = 65$) were located in the currently known pancreatic cancer risk loci identified in subjects of European descent (for genes located ± 100 kb from the most significant SNP at the 22 risk loci) based on KEGG, Gene Ontology (Biological Process and Molecular Function) annotations using GeneCodis3 with reporting of FDR-corrected hypergeometric P values (Supplementary Table 8)⁵⁶.

Replication. Ten promising signals ($P < 10^{-6}$) were selected for replication in samples from the PANDoRA consortium²³. Genotyping was performed by custom TaqMan genotyping assays (Applied Biosystems) at the German Cancer Research Center (DKFZ) in Heidelberg, Germany, for 2770 pancreatic cancer patients and 5178 controls, of which 2737 cases and 4753 controls had complete age and clinical data and did not overlap with other study individuals. Duplicate quality-control samples ($n = 607$ pairs) showed 99.48% genotype concordance. SNP quality metrics

were performed for each SNP by plate; plates with <80% genotype completion rates were dropped from the analysis. Individuals were excluded if they were missing data on two or more SNPs after excluding SNPs on plates with low genotype completion rates. The association analysis for PANDoRA was adjusted for age and study in the same manner as previously described^{14–16}. Heterogeneity between studies was assessed using the Cochran’s Q-test. Association analysis was also performed for the set of variants previously replicated in PANDoRA as part of the PanScan III¹⁴ and PanC4¹⁶ GWAS studies (Supplementary Table 3).

Using SequenLdhot, recombination hotspots for association plots were generated as previously described^{12–14}. Recombination hotspot inference was performed using the 1000 G CEU samples ($n = 99$). The LD heatmap was prepared using the 1000 G Phase 3 CEU data, and the *snplot* R software package⁶³.

eQTL analysis. The publicly available GTEx data⁶⁴ (<http://www.gtexportal.org/>; version 6) were used to assess eQTLs in pancreatic tissue samples ($n = 149$). RefSeq genes located within ± 500 kb of the marker SNP for each GWAS significant locus were assessed for *cis*-eQTL effects. Nominally significant eQTLs from this analysis ($P < 0.05$) were then taken forward to further analysis in two additional pancreatic tissue sample sets⁵⁸: (1) the LTG and (2) The Cancer Genome Atlas (TCGA) pancreatic adenocarcinoma (PAAD) samples.

The LTG set included 95 histologically normal pancreatic tissue samples from participants of European ancestry collected at three participating sites: Mayo Clinic in Rochester, MN (45 samples, adjacent to tumor); Memorial Sloan Kettering Cancer Center in New York City, NY (34 samples, adjacent to tumor); and Penn State College of Medicine, Hershey, PA (16 samples, from tissue donors via the Gift of Life Donor Program, Philadelphia, PA) as previously described⁵⁸. Samples were

confirmed to be non-tumorous with $\geq 80\%$ epithelial component by histological review and macro-dissected when needed. The project was approved by the Institutional Review Board of each participating institution as well as the NIH.

In short, RNA (RIN > 7.5) isolated from fresh frozen histologically normal pancreatic tissue samples (LTG samples) with the Ambion mirVana kit was poly-A-enriched and subjected to massively parallel paired-end sequencing (Illumina's HiSeq2000/TruSeq v3 sequencing). MapSplice was used to align reads and RSEM (v1.2.14) for gene expression quantification (TPM)^{65,66} using the hg19/GRCh37-based UCSC "RefSeq" track for gene annotation. DNA for genotyping was isolated from blood (Mayo Clinic samples), histologically normal fresh frozen pancreatic tissue samples (Penn State samples), or histologically normal fresh frozen spleen or duodenum tissue samples (MSKCC samples) using the Genra Puregene Tissue Kit (Qiagen). DNA samples were genotyped on the Illumina OmniExpress or Omni1M arrays at the CGR of the Division of Cancer Epidemiology and Genetics, NCI, NIH. After quality control, genotypes were imputed using the 1000 G (Phase 1, v3) imputation reference data set and IMPUTE 2⁶⁷. Pre-imputation exclusion filters of Hardy Weinberg Equilibrium $P < 1 \times 10^{-6}$, minor allele frequency (MAF) < 0.01 , genotype missing rate > 0.05 , A/T and G/C pairs on ambiguous DNA strand (MAF > 0.45), and significantly different allele frequency between sample data and the 1000 G reference data ($P < 7 \times 10^{-8}$; Fisher's exact test) were used. Post-imputation variants (single-nucleotide variants (SNP) and small insertion-deletion (indel) polymorphisms) with MAF < 0.05 or imputation quality scores (INFO score) < 0.5 were removed from the final analysis⁵⁸.

The second sample set included RNA-sequencing (RNA-seq) and genotype data from tumor-derived pancreatic samples obtained from TCGA PAAD data set by permission through the TCGA Data Access Committee. We excluded samples of non-European ancestry, with history of neo-adjuvant therapy prior to surgery, or with histological subtypes other than PDAC, leaving a total of 115 tumor samples for analysis⁵⁸. TCGA mRNA-seq data (level 1 read data, generated using Illumina's HiSeq2000) for pancreatic cancer samples (TCGA PAAD) were processed in the same manner as the histologically normal LTG samples described above. Blood-derived DNA samples for TCGA PAAD samples were genotyped on Affymetrix 6.0 arrays and processed in the same manner as for the LTG samples⁵⁸.

The eQTL analysis was performed separately in histologically normal (LTG) and tumor-derived (TCGA PAAD) pancreatic samples using the Matrix eQTL (http://www.bios.unc.edu/research/genomic_software/Matrix_eQTL/) software package⁶⁸. We tested associations between genotyped and imputed SNPs and the expression of genes evaluated by mRNA-sequencing after upper quantile normalization within samples and normal quantile transformation for each gene across samples by regressing the imputed dosage of the minor allele for each variant against normalized gene expression values⁶⁸. Linear models were adjusted for age, sex, study, and the top five principal components (PCs) each for genotypes and gene expression to account for possible measured or hidden confounders⁵⁸. The T-statistics from the linear regression is reported. For the tumor samples, we further adjusted for tumor stage and sequence-based tumor purity as per information provided by TCGA.

Bioinformatic analysis of functional potential. Variants at the new risk loci were assessed for potential functionality by examining their location in open (DNase Hypersensitivity Regions, DHS) and active chromatin (as per promoter and enhancer histone modification marks) in the ENCODE data. For this, we used HaploReg 4.1 (<http://www.broadinstitute.org/mammals/haploreg/haploreg.php>) and the UCSC Genome Browser (<http://genome.ucsc.edu/>). Variants correlated with the most significant variant at each locus at $r^2 > 0.7$ in 1000 G EUR populations were included, except for 1p36.33/NOC2L where P value LR $> 1:100$ was used.

Candidate functional variants at 1p36.33 were selected by comparing the likelihood of each variant from the association analysis with the likelihood of the most significant variant. Ten variants had likelihood ratios, LR $> 1:100$ relative to the most significant SNP: rs13303010 (P value rank 1), rs13303327 (rank 2), rs113491766 (rank 3), rs3935066 (rank 4), rs111748052 (rank 5), rs10465242 (rank 6), rs13303160 (rank 7), rs7524174 (rank 8), rs13302957 (rank 9), and rs4970445 (rank 10). They were all highly correlated with rs13303010 ($r^2 = 0.52-1.00$, 1000 G EUR data). These 10 variants were considered the set of variants most likely to contain the functional variant(s) at 1p36.33. Possible allelic effects of these top 10 variants on TF-binding motifs were determined using PrEdict Regulatory Functional Effect of SNPs by Approximate P value Estimation (PERFECTOS-APE; <http://opera.autosome.ru/perfectosape/>) analysis that determines the probability of a TF motif (using position weight matrices, from HOCOMOCO-10, JASPAR, HT-SELEX, SwissRegulon, and HOMER databases) in the DNA sequence overlapping each variant. The fold change in probability of there being a TFBS present for each allele of a variant is then calculated⁶⁹. Two dbSNP variants at 1p36.33 with the same bp location, rs111748052 (=ATTTT) and rs10465241 (C/T), may be two independent variants (as indicated in dbSNP), or a single tri-allelic marker (alleles are shown as C/CATTTT/T in 1000 G). As PERFECTOS-APE does not analyze indel variants, we analyzed the two indels among the 10 potential functional variants, rs111748052 and rs113491766, using a different program, sequence TF Affinity Prediction. This program calculates the total affinity of a sequence for a TF (as given by TRANSFAC and JASPAR databases) on the basis of a biophysical model of the binding energies between a TF and DNA⁷⁰. The probability for a

given TFBS for each variant of the indel was then compared as in PERFECTOS-APE to determine the fold change effect of the indel on the presence of the TFBS.

Gene expression analysis. Gene expression was assessed for genes that are closest to the reported variants at chromosomes 1p36.33: *NOC2L*, *KLHL17*, and *PLEKHNI1*; 7p12: *TNS3*; 8q21.11: *HNF4G*; 17q12: *HNF1B*; 18q21.32: *GRP*, as well as two additional genes at 1p36.33 exhibiting nominally significant eQTLs in GTEx (1p36.33/*SAMD11/DVLI1*). We assessed differential expression of these genes in pancreatic tumor samples (PDAC, $n = 8$), histologically normal (non-malignant) pancreatic tissue samples ($n = 10$), and pancreatic cell lines ($n = 9$) by RNA-seq as described previously⁴⁴. We compared gene expression in tumors (T) and cell lines (C) to histologically normal pancreatic tissue samples (N) by EdgeR analysis. P values for differential expression in tumor vs. normal (TvN) and Cell lines vs. normal (CvN) represent an exact statistic using the normalized pseudo-counts and tagwise dispersion estimates per gene.

Data availability. The PanScan and PanC4 genome-wide association data that support the findings of this study are available through dbGAP (accession numbers phs000206.v5.p3 and phs000648.v1.p1, respectively).

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A.P.K., R.S.S., L.T.A., B.M.W., G.M.P., and H.A.R. organized and designed the study. A.P.K., L.T.A., F.C., J.W.H., A.J., J.Z., and M.B. organized and supervised the genotyping of samples. E.J.C., E.M., O.O., M.Z., A.Blackford, L.T.A., F.C., P.K., J.W.H., A.J., J.Z., F. Chen, and A.P.K. designed and conducted the statistical analysis. A.P.K. and L.T.A. drafted the first version of the manuscript. A.P.K., B.M.W., H.A.R., R.Z.S.-S., F.C., D.A., G.A., A.A.A., A.B., W.R.B., L.B.-F., S.L.B., A.Borgida, P.M.B., L.B., P.B., H.B., B.B.-d.-M., J.B., D.C., G.C., G.C., G.M.C., K.G.C., C.C.C., S.C., M.C., F.D., E.J.D., L.F., C.F., N.F., S.G., J.M.M.G., M.Gazouli, G.G.G., E.G., M.G., G.E.G., P.J.G., T.H., C.H., P.H., M.H., P.H., K.J. H., J.H., I.H., E.A.H., R.H., R.J.H., E.J.J., K.J., V.J., R.K., K.-T.K., E.A.K., M.K., C.K., M.H. K., J.K., R.J.K., D.L., S.L., R.T.L., I.-M.L., L.L., L.Lu, N.M., A.M., S.M., R.L.M., B.M.-D., R. E.N., J.P.N., A.L.O., I.O., C.P., A.V.P., U.P., R.P., M.P., F.X.R., N.R., G.S., H.D.S., G.S., X.-O.S., D.S., J.P.S., P.S., M.S., R.T.-W., F.T., M.D.T., G.S.T., S.K.V., Y.V., K.V., P.V., J.W.-W., Z.W., N.W., E.W., H.Y., K.Y., A.Z.-J., W.Z., P.K., D.L., S.C., O.O., G.M.P., and L.T.A. conducted the epidemiological studies and contributed samples to the GWAS, expression and/or follow-up genotyping. All authors contributed to the writing of the manuscript.

Additional information

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