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A genome-wide meta-analysis identifies 22 loci associated with eight hematological parameters in the HaemGen consortium

Nicole Soranzo^{1,2,45}, Tim D Spector^{2,45}, Massimo Mangino^{2,45}, Brigitte Kühnel³, Augusto Rendon⁴, Alexander Teumer⁵, Christina Willenborg^{6,7}, Benjamin Wright⁸, Li Chen⁹, Mingyao Li¹⁰, Perttu Salo^{11,12}, Benjamin F Voight^{13,14}, Philippa Burns⁴, Roman A Laskowski¹⁵, Yali Xue¹, Stephan Menzel¹⁶, David Altshuler^{13,14,17,19}, John R Bradley²⁰, Suzannah Bumpstead¹, Mary-Susan Burnett²¹, Joseph Devaney²¹, Angela Döring³, Roberto Elosua²², Stephen Epstein²¹, Wendy Erber²³, Mario Falchi^{24,2}, Stephen F Garner⁴, Mohammed J R Ghorri¹, Alison H Goodall²⁵, Rhian Gwilliam¹, Hakon H Hakonarson²⁶, Alistair S Hall²⁷, Naomi Hammond¹, Christian Hengstenberg²⁸, Thomas Illig³, Inke R König⁶, Christopher W Knouff²⁹, Ruth McPherson⁹, Olle Melander³⁰, Vincent Mooser²⁹, Matthias Nauck³¹, Markku S Nieminen³², Christopher J O'Donnell^{33,18}, Leena Peltonen^{11,12}, Simon C Potter¹, Holger Prokisch^{34,35}, Daniel J Rader^{36,37}, Catherine M Rice¹, Robert Roberts⁹, Veikko Salomaa^{11,12}, Jennifer Sambrook⁴, Stefan Schreiber³⁸, Heribert Schunkert⁷, Stephen M Schwartz^{39,40}, Jovana Serbanovic-Canic⁴, Juha Sinisalo³², David S. Siscovick^{39,40}, Klaus Stark²⁸, Ida Surakka¹², Jonathan Stephens⁴, John R Thompson⁸, Uwe Völker³⁸, Henry Völzke⁴¹, Nicholas A Watkins⁴, George A Wells⁹, H-Erich Wichmann^{3,42}, David A Van Heel⁴³, Chris Tyler-Smith¹, Swee Lay Thein¹⁶, Sekar Kathiresan^{33,18}, Markus Perola^{11,12}, Muredach P Reilly^{36,37}, Alexandre F R Stewart⁹, Jeanette Erdmann⁷, Nilesh J Samani²⁵, Christa Meisinger³, Andreas Greinacher⁴⁴, Panos Deloukas^{1,45}, Willem H Ouwehand^{4,1,45}, and Christian Gieger^{3,45}

¹ Human Genetics, Wellcome Trust Sanger Institute, Genome Campus, Hinxton, UK ² Department of Twin Research and Genetic Epidemiology, King's College London, London, UK ³ Institute of Epidemiology, Helmholtz Zentrum München, German Research Center for Environmental Health, Neuherberg, Germany ⁴ Department of Haematology, University of Cambridge and National Health Service Blood and Transplant, Cambridge, UK ⁵ Interfakultäres Institut für Genetik und Funktionelle Genomforschung, Ernst-Moritz-Arndt-Universität Greifswald, Greifswald, Germany ⁶ Institut für Medizinische Biometrie und Statistik ⁷ Medizinische Klinik II, Universität zu Lübeck, Lübeck, Germany ⁸ Department of Health Sciences, University of Leicester, Leicester, UK ⁹ John & Jennifer Ruddy Canadian Cardiovascular Genetics Centre, University of Ottawa Heart Institute, Ottawa, Ontario, Canada ¹⁰ Department of Biostatistics and

Correspondence should be addressed to N.S. (ns6@sanger.ac.uk).

⁴⁵These authors contributed equally to this work.

AUTHOR CONTRIBUTIONS

Manuscript preparation: N.S., M.M., A.R., W.H.O., T.D.S., P.D., N.J.S., C.G. Main data analysis: N.S., C.G., B.K., A.R., A.T., R.A.L., Y.X., C.T.-S.

Intermediate trait analysis cohorts. *Study design and biobanking:* T.D.S. (TwinsUK), J.R.B., W.E., S.F.G., J.S.-C., J. Sambrook, N.A.W., W.H.O. (UKBS-CC1 and CBR), C.G., T.I., H.-E.W. (KORA F3 and F4), M.N., U.V., H.V. (SHIP). *Phenotype assessment:* S.M., M.F., S.L.T., T.D.S. (TwinsUK), A.D., C.M. (KORA F3 and F4), A.G. (SHIP). *Genotyping:* R.G., S.C.P., C.M.R., P.D. (TwinsUK), S.B., M.J.R.G., R.G., N.H., J.Stephens (CBR), H.P., T.I. (KORA F3 and F4). *Statistical analysis:* N.S. (TwinsUK), N.S. (CBR), N.S. (UKBS-CC1), C.G., B.K. (KORA F3 and F4), A.T. (SHIP), A.R., P.B. (Transcriptomics).

CAD/MI cohorts. *GerMIFS I and GerMIFS II:* C.H., I.R.K., S.S., K.S., C.W., H.-E.W., C.W., J.E., H.S. *WTCCC-CAD:* N.J.S., A.H.G., A.S.H., B.W., J.R.T. *Ottawa Heart Study:* L.C., R.M., R.R., G.A.W., A.F.R.S. *PennCATH/MedSTAR:* M.L., M.S.B., J.D., S.E., H.H.H., D.J.R., M.P.R., V.M., C.W.K. *MIGEN:* S.K., B.F.V., S.M.S., V.S., R.E., O.M., C.J.O., L.P., D.S.S., D.A. *COROGENE:* M.P., P.S., V.S., L.P., I.S., J.Sinisalo, M.S.N. **Celiac disease.** D.A.V.H.

Epidemiology, University of Pennsylvania, Philadelphia, Pennsylvania, USA ¹¹ Chronic Disease Prevention, National Institute for Health and Welfare, Helsinki, Finland ¹² The Institute of Molecular Medicine, University of Helsinki, Finland ¹³ Center for Human Genetic Research, Massachusetts General Hospital, Boston, Massachusetts, USA ¹⁴ Program in Medical and Population Genetics, Broad Institute of MIT and Harvard, Cambridge, Massachusetts, USA ¹⁵ European Bioinformatic Institute, Genome Campus, Hinxton, UK ¹⁶ Department of Haematology, King's College London, London, UK ¹⁷ Department of Molecular Biology, Massachusetts General Hospital, Boston, Massachusetts, USA ¹⁸ Department of Medicine, Harvard Medical School, Boston, Massachusetts, USA ¹⁹ Department of Genetics, Harvard Medical School, Boston, Massachusetts, USA ²⁰ Department of Medicine, University of Cambridge School of Clinical Medicine, Addenbrooke's Hospital, Cambridge, UK ²¹ Cardiovascular Research Institute, MedStar Research Institute, Washington Hospital Center, Washington, DC, USA ²² Cardiovascular Epidemiology and Genetics, Institut Municipal D'investigacio Medica and CIBER Epidemiologia y Salud Pública, Barcelona, Spain ²³ Haematology Department, Cambridge University Hospitals NHS Foundation Trust, Cambridge, UK ²⁴ Genomic Medicine, Imperial College London, South Kensington Campus, London, UK ²⁵ Cardiovascular Sciences, University of Leicester, Glenfield Hospital, Leicester, UK ²⁶ The Center for Applied Genomics, Children's Hospital of Philadelphia, Philadelphia, Pennsylvania, USA ²⁷ BHF Heart Research Centre, Clinical Cardiology, Leeds General Infirmary, Leeds, UK ²⁸ Klinik und Poliklinik für Innere Medizin II, Universität Regensburg, Regensburg, Germany ²⁹ Genetics Division, GlaxoSmithKline King of Prussia, Pennsylvania, USA ³⁰ Department of Clinical Sciences, Hypertension and Cardiovascular Diseases, University Hospital Malmö, Lund University, Malmö, Sweden ³¹ Institut für Klinische Chemie und Laboratoriumsmedizin, Ernst-Moritz-Arndt Universität Greifswald, Greifswald, Germany ³² Department of Medicine, Division of Cardiology, Helsinki University Central Hospital, Helsinki, Finland ³³ Cardiovascular Research Center and Cardiology Division, Massachusetts General Hospital, Boston, Massachusetts, USA ³⁴ Department of Human Genetics, Klinikum rechts der Isar, Technical University Munich, Munich, Germany ³⁵ Institute of Human Genetics, Helmholtz Zentrum München, German Research Center for Environmental Health, Neuherberg, Germany ³⁶ The Cardiovascular Institute, University of Pennsylvania, Philadelphia, Pennsylvania, USA ³⁷ The Institute for Translational Medicine and Therapeutics School of Medicine University of Pennsylvania, Philadelphia, Pennsylvania, USA ³⁸ Institut für Klinische Molekularbiologie, Christian-Albrechts Universität, Kiel, Germany ³⁹ Cardiovascular Health Research Unit, Departments of Medicine and Epidemiology, University of Washington, Seattle, Washington, USA ⁴⁰ Department of Epidemiology, University of Washington, Seattle, Washington, USA ⁴¹ Institute for Community Medicine, Ernst-Moritz-Arndt-Universität Greifswald, Greifswald, Germany ⁴² Institute of Medical Informatics, Biometry and Epidemiology, Ludwig-Maximilians-Universität, Munich, Germany ⁴³ Institute of Cell and Molecular Science, Barts and The London School of Medicine and Dentistry, London, UK ⁴⁴ Institut für Immunologie und Transfusionsmedizin, Ernst-Moritz-Arndt-Universität Greifswald, Greifswald, Germany

Abstract

The number and volume of cells in the blood affect a wide range of disorders including cancer and cardiovascular, metabolic, infectious and immune conditions. We consider here the genetic variation in eight clinically relevant hematological parameters, including hemoglobin levels, red and white blood cell counts and platelet counts and volume. We describe common variants within 22 genetic loci reproducibly associated with these hematological parameters in 13,943 samples from six European population-based studies, including 6 associated with red blood cell parameters, 15 associated with platelet parameters and 1 associated with total white blood cell count. We further identified a long-range haplotype at 12q24 associated with coronary artery disease in 9,479 cases and 10,527 controls. We show that this haplotype demonstrates extensive disease pleiotropy, as it contains known risk loci for type 1 diabetes, hypertension and celiac

disease and has been spread by a selective sweep specific to European and geographically nearby populations.

The hematopoietic system is one of the best-studied cellular differentiation processes in mammals. The differentiation of the hematopoietic stem cell into its progeny is a tightly orchestrated process of fate determination and cell proliferation which results in a repertoire of different types of mature cells in the peripheral blood that supervise a range of functions including the transport of oxygen, innate and adaptive immunity, vessel wall surveillance, homeostasis and wound repair. The count and volume of the cellular elements in circulating blood are highly heritable and tightly regulated^{1,2} and vary widely between individuals. Such hematological traits, which include the concentration of hemoglobin (Hb), the numbers of white blood cells (WBC), red blood cells (RBC) and platelets (PLT), and the volumes of red blood cells and platelets (MCV and MPV, respectively), are commonly used parameters in the clinic. Deviations outside normal ranges for these parameters are indicative of many different disorders including cancer and infectious and immune diseases. Multiple reports confirm that high white cell counts are an independent risk factor for coronary artery disease (CAD) and myocardial infarction (MI)³⁻⁵. Increased platelet volume has also been variably associated with MI risk⁶.

We established the HaemGen Consortium in order to search for genetic loci contributing to variation in hematological parameters and to assess the potential correlation of these loci with disease phenotypes. In an initial cross-replication analysis of two independent genome-wide association (GWA) studies, we described four loci associated with MPV in Europeans. The four loci map in or near *WDR66* (rs7961894), *ARHGEF3* (rs12485738), *TAOK1* (rs2138852) and *PIK3CG* (rs342293) and account for approximately 5.5% of the genetic variance^{7,8} in MPV. Here, we describe the findings of the first systematic genome-wide meta-analysis with independent replication of a broader range of eight clinically relevant hematological traits. We report 22 loci associated with these traits, one of which is also associated with increased risk of CAD.

RESULTS

GWA analysis of hematological parameters

The study design is shown in Figure 1. We analyzed a total of eight hematological parameters. Six of these parameters are measured directly: Hb, RBC and MCV for red cells, PLT and MPV for platelets and WBC for white cells. In addition, we tested the two derived red cell measures of mean corpuscular hemoglobin content (MCH) and mean corpuscular hemoglobin concentration (MCHC). Although they are derived from, and thus correlated to, the three measured red cell traits, we included MCH and MCHC because they are commonly used in the differential diagnosis of anemia.

We implemented a two-stage design involving a discovery set of 4,627 individuals sampled from three population-based samples and a replication set of 9,316 individuals from three additional studies (Fig. 1). All participants were of European ancestry. The characteristics of each sample collection are described in Supplementary Table 1a. After we applied stringent quality control criteria as described in the Supplementary Note, 2.11 million genotyped and imputed autosomal SNPs were available for analysis in all the three stage 1 samples. A uniform analysis plan was applied to each cohort, and individual summary statistics were combined using an inverse variance meta-analysis. There was no evidence of inflation of the summary statistics across the eight traits in the three discovery cohorts (Supplementary Note).

Following meta-analysis, we applied additional filtering criteria as described in the Online Methods to prioritize genomic regions for replication. A total of 88 independent regions met these criteria across the eight traits, including 11 for Hb, 10 for MCH, 3 for MCHC, 12 for MCV, 12 for RBC, 25 for MPV, 8 for PLT and 7 for WBC (Fig. 2). In each region we selected the SNP with the lowest P value for follow-up in the replication samples ('leading SNP'). For one locus on chromosome 12q24, we selected two SNPs for follow-up (rs11065987 and rs11066301) that were in high linkage disequilibrium (LD) with each other ($r^2 = 0.82$) but were located >500 kb apart (specifically, the two SNPs are 799 kb apart). The replication set included 9,316 individuals from three European population-based studies (Supplementary Table 1a). We applied the same uniform analysis plan and meta-analytical approach described in the Online Methods for analysis of the replication datasets and for combining summary statistics.

Characterization of 22 loci associated with hematological parameters

Of the 89 SNPs with replication data, 23 SNPs from 22 regions (including both SNPs in the 12q24 region) had nominally significant P values in the replication sample and reached genome-wide significance at the threshold of 5×10^{-8} in the combined sample of 13,943 individuals (Table 1; the summary statistics for loci that did not reach this threshold are given in Supplementary Table 2). Of the 22 loci, 7 are known loci for hematological parameters and the remaining 15 identify new association signals. We searched published literature, databases of mendelian human disease (Online Mendelian Inheritance in Man), gene function and homology with animal models of function and disease in order to prioritize the most likely candidate genes (Supplementary Table 3). Furthermore, we characterized the expression patterns of all the genes within a 1-Mb interval from the lead SNP in eight blood cell lines and endothelial cells using Illumina HumanWG-6 (v2) Expression BeadChip expression arrays (Supplementary Fig. 1 and Supplementary Note). Finally, for platelet loci, we also tested associations with transcript level in a panel of 35 platelet mRNAs. Although this effort provides supplementary evidence to prioritize a list of the most plausible candidates in each region, we note that more in-depth characterization will be required in order to conclusively associate genes with the observed phenotypic variation.

Red blood cell traits—Six independent regions were confirmed as strongly associated with red blood cell parameters with all exerting their main effect on MCV or RBC (Table 1). Among these regions were two well-characterized loci: the *HBS1L-MYB* region on 6q23–q24 (rs9402686, $P = 7.4 \times 10^{-42}$) and the C282Y amino acid change in *HFE* at 6p21.3 (rs1800562, $P = 1.4 \times 10^{-23}$). Rare nonsynonymous mutations in these genes have been associated with hereditary hemochromatosis and common SNPs with measures of iron status (Supplementary Table 3). Of the red cell loci, the *HBS1L-MYB* locus had the greatest pleiotropic effect, showing genome-wide significant associations with MCH ($P = 4.5 \times 10^{-40}$), RBC ($P = 1.6 \times 10^{-29}$), PLT ($P = 2.2 \times 10^{-13}$) and, to a lesser extent, MCHC ($P = 1.2 \times 10^{-5}$) and WBC ($P = 6.3 \times 10^{-5}$; Supplementary Table 4). Two other association signals were located near genes known to play a role in iron hemostasis (*TMPRSS6* and *TFR2*). The serine protease matriptase-2, encoded by *TMPRSS6* (lead SNP rs5756506, $P = 9.5 \times 10^{-10}$), regulates levels of the peptide hormone hepcidin, the master regulator of iron homeostasis in humans⁹. The rs5756506 SNP was the only red-blood-cell locus to be strongly associated with Hb levels ($P = 3.4 \times 10^{-8}$, Supplementary Table 4); the only other red blood cell locus with a nominal effect on Hb was *HFE* ($P = 1.6 \times 10^{-4}$). The signal on chromosome 7q22 (rs7385804, $P = 4.9 \times 10^{-10}$) is centered on the *TFR2* gene, which encodes the type-2 transferrin receptor essential to cellular uptake of transferrin-bound iron¹⁰. Another likely candidate in this gene-dense region is *EPO* (erythropoietin), a growth factor critical for fate determination within the erythroid lineage¹¹. Another newly identified

MCV locus on chromosome 6p21.1 (rs11970772, $P = 7.0 \times 10^{-19}$) maps to a recombination interval near the *BYSL* and *CCND3* genes. We found that five out of the seven genes in the *BYSL-CCND3* region were abundantly transcribed in hematopoietic cells (Supplementary Fig. 1). Both *BYSL* and *CCND3* have roles in hematopoiesis (Supplementary Table 3). *BYSL* (bystin) is a target of c-MYC mRNA, which is consistent with a role in rapid protein synthesis required for actively growing cells¹². *Ccnd3*^{-/-} mice show lethality due to heart abnormalities combined with severe anemia¹³. Finally, the association signal for MCV at 22q12–q13 overlaps with *FBXO7* (rs9609565, $P = 4.3 \times 10^{-10}$), a gene highly expressed in erythroblasts (EBs), which are the precursors of red blood cells (Supplementary Fig. 1).

White blood cell counts—One association signal for the total number of leukocytes was identified on 17q12 near *GSDMA-ORMDL3* (rs17609240, $P = 9.4 \times 10^{-9}$), a known susceptibility locus for childhood asthma¹⁴. Notably, this locus contains *CSF3*, which encodes colony stimulating factor 3, a cytokine controlling the production, differentiation and function of granulocytes¹⁵.

Platelet counts and mean platelet volume—In addition to the four loci associated with MPV (*WDR66*, *ARHGEF3*, *TAOK1* and *PIK3CG*) previously described by our groups^{7,8}, we detected eight new loci associated with MPV and the first three loci found to be associated with PLT (Table 1, Supplementary Fig. 1). Nine of the 12 MPV loci were also associated with PLT, of which 3 reached genome-wide significance in the combined sample. In all cases the MPV-raising alleles were associated with a decrease in PLT (Supplementary Table 4). Conditional analyses show however that all SNPs exerted their main effects through MPV (Online Methods).

Of the newly identified MPV-associated loci, the association signals on chromosome 1q24.3 (*DNM3*, rs10914144, $P = 2.1 \times 10^{-14}$) and 18q22.3 (*CD226*, rs893001, $P = 1.5 \times 10^{-10}$) contained two strong and highly plausible candidate genes with a known role in megakaryocyte (MK) development (Supplementary Table 3) and enhanced gene expression in MKs when compared with EBs (Supplementary Fig. 1). Four additional regions map in or near *JMJD1C* (rs2393967, $P = 3.3 \times 10^{-21}$), *TPM1* (rs11071720, $P = 1.9 \times 10^{-8}$), *SIRPA* (rs6136489, $P = 7.7 \times 10^{-11}$) and *EHD3* (rs647316, $P = 3.2 \times 10^{-11}$), which are candidates with indirect evidence for a role in hematopoiesis in humans (as discussed in Supplementary Table 3). Of these genes, *JMJD1C* (10q21) encodes a probable histone demethylase, with a possible function in hormone-dependent transcriptional activation. Mouse mutated at *Jmjd1c* (encoding Jumonji domain containing 1C) display increased proliferation of MK lineage cells¹⁶. *TPM1* encodes tropomyosin I, which regulates the calcium-dependent interaction of actin and myosin, a key step in platelet formation. *TPM1* was found to be highly downregulated in an individual with a unique mutation in *RUNX1* (also called *CBFA2*) and a severe platelet function disorder¹⁷. Finally, two newly identified regions at 1q32.1 and 11p15.5 are gene rich, and further efforts will be required to identify the most likely gene candidates for association with MPV. The 11p15.5 signal maps to a region proximal to the genes *BETIL*, *SIRT3* and *PSMD13* (among others). In this region, we found evidence that the lead SNP rs11602954 affects expression of the two neighboring genes *BETIL* (Spearman's test $P = 3.1 \times 10^{-5}$) and *SIRT3* ($P = 2.8 \times 10^{-5}$) as well as *PSMD13* to a lesser degree ($P = 7.3 \times 10^{-3}$, see Supplementary Note and Supplementary Fig. 1). A G477T variant in its promoter has been shown to co-regulate *SIRT3* and *PSMD13* and has been linked to longevity in humans¹⁸. Three independent loci with effects on PLT were identified. The association signal on the 6p21.3 locus was centered in the *BAK1* gene (rs210135, $P = 3.7 \times 10^{-10}$), which encodes a protein with a strong proapoptotic effect that is known to control platelet lifespan¹⁹. Two further SNPs map to 12q24.12 (rs11065987, $P = 2.2 \times 10^{-13}$ and rs11066301, $P = 7.7 \times 10^{-12}$). The association signal on 12q24.12 spans ~1.6 Mb and harbors 15 genes including *PTPN11*, *SH2B3* and *BRAP*. This region is

discussed in more detail below. Finally, an association signal at 9p24.1–p24.3 (rs385893, $P = 8.5 \times 10^{-17}$) was found 400 kb upstream of *JAK2*, which is a key regulator of megakaryocyte maturation and is somatically mutated in half of the individuals with essential thrombocytosis²⁰.

Multimarker scores

Overall, the fraction of genetic variance explained by each locus in regression models adjusted for sex and age was 8.6% for MPV traits, 0.5% for PLT traits, 3% for erythrocyte traits and 0.12% for the single validated WBC locus. We constructed a score to predict MPV levels from the joint model of the 12 validated MPV SNPs and the 6 validated SNPs associated with red blood cell traits as described in the Online Methods section (Fig. 3). The regression of mean on score indicates an average increase of MPV of 0.12 fl per copy of a MPV-increasing allele and 0.47 fl per copy of a MCV-increasing allele.

Associations with coronary artery disease

Because several of the hematological traits analyzed show an association with CAD or MI, we examined the association of the validated 23 SNPs (including the two associated SNPs on 12q24.12) with CAD. We used a two-stage approach to test for association with CAD (Fig. 1). First, we obtained association statistics for 4,021 affected individuals (cases) and 5,879 controls from three European CAD or MI case-control studies (Wellcome Trust Case Control Consortium (WTCCC)-CAD, German Myocardial Infarction Family Study (GerMIFS I and GerMIFS II) and calculated the pooled odds ratios. All studies included validated cases of premature MI or CAD as detailed in Supplementary Table 1b and the Supplementary Note. Two SNPs from one region (SNPs rs11066301 and rs11065987 on 12q24) had nominal significance ($P \leq 0.05$) in the stage 1 analysis (Supplementary Table 5). For these loci, we obtained summary statistics from an additional 5,458 cases and 4,648 controls from five further case-control collections, including the Ottawa Heart, MedSTAR, PennCATH, MIGen and the COROGENE studies. All samples had a validated diagnosis of CAD (including MI) compatible with the clinical criteria used in the stage 1 samples (See Supplementary Table 1b and Supplementary Note for case definition in the different studies).

The association results for the two SNPs rs11066301 and rs11065987 on 12q24 were strongly replicated in the stage 2 sample, providing independent confirmation for 12q24 as a risk locus for CAD. In the combined sample of 9,479 cases and 10,527 controls, the allelic odds ratios of rs11066301 (minor allele frequency (MAF) = 0.35) and rs11065987 (MAF = 0.34) were, respectively, 1.144 (95% CI 1.095–1.196, $P = 2.52 \times 10^{-9}$) and 1.152 (95% CI 1.104–1.202, $P = 7.05 \times 10^{-11}$ Fig. 4 and Supplementary Table 5a); the respective allelic odds ratios for a MI sub-analysis were 1.165 (95% CI 1.111–1.222], $P = 3.43 \times 10^{-10}$) and 1.177 (95% CI 1.124–1.231, $P = 2.42 \times 10^{-12}$; Supplementary Table 5b). For both SNPs, the minor allele was associated with increased PLT and risk of CAD and MI. The same association with CAD was recently reported by an independent study²¹.

Haplotype structure of the 12q24 locus, natural selection and pleiotropic effects in human disease

The SNPs rs11065987 and rs11066301 are located 799 kb apart and are in high LD ($r^2 = 0.82$). Analysis of the PLT association plot shows that the signals map to two adjacent recombination intervals spanning approximately 1.6 Mb and containing 15 genes. The expression of such genes in blood lineages is shown in Figure 5. The haplotype structure of this region is shown in Figure 6. We analyzed the local LD pattern in three HapMap population panels (CEU, CHB+JPT, YRI). In the CEU panel, the region is characterized by extended LD. Ten common SNPs (MAF = 0.35–0.4) identify a common haplotype spanning

the length of the associated interval (Table 2). Of the ten SNPs, one is an Arg262Trp nonsynonymous change in the gene *SH2B3* (rs3184504), seven are intronic within four genes (*ATXN2*, *C12orf30*, *C12orf51* and *PTPN11*) and two are intergenic. All of them display genome-wide significant association with PLT (Fig. 6a). We calculated the pooled summary statistics for associations with CAD in the same 1.6 Mb region using six of the eight case-control studies with available data. The ten SNPs had similarly elevated *P* values for association with CAD (Table 2, see also Supplementary Table 5), whereas the remaining SNPs in the region did not show strong association with CAD (Fig. 6b). The G allele at rs17696736 in *C12orf30* is a known risk factor for type 1 diabetes (T1D)^{22,23}. A second SNP on the same haplotype (rs3184504 in *SH2B3*) has been previously associated with celiac disease, whereby the CAD risk allele also increases risk for celiac disease²⁴. We retrieved association data for T1D and celiac disease generated in previous studies (Supplementary Note) and plotted the association statistics for genotyped and imputed SNPs over the same interval (Fig. 6c,d). We observed a similar elevation of the association signals at the ten SNPs (where present), which suggests a pattern of association similar to PLT and CAD.

We retrieved the ancestral states by comparison with chimpanzee data from the University of California at Santa Cruz genome browser for each of the ten SNPs showing significant association with PLT (Table 2). The CAD-risk and PLT-raising alleles corresponded to the derived states. We retrieved the integrated haplotype score (iHS)^{25,26} and Fay and Wu's *H+* statistics for HapMap Phase II data (Table 2)^{25–27} to test the hypothesis that the long-range, evolutionarily derived haplotype in this region arose from a positive selection event—that is, a selective sweep. The 12q24 region showed a signature characteristic of a selective sweep, with highly negative iHS scores (−4.341 to −2.756, an extreme pattern compared to an empirical genome-wide threshold of −2 for positive selection²⁵) and highly skewed Fay and Wu's *H+* statistics (Table 2). Accordingly, the extended haplotype homozygosity statistics²⁸ show excess homozygosity on the evolutionarily derived haplotype over a 1.6-Mb interval (Fig. 6g). We estimated the age of the rs3184504 T-allele haplotype²⁵ at approximately 3,400 years (Supplementary Note). Next, we compared the population differentiation statistics F_{ST} at the 10 SNPs with the empirical distributions of frequency-matched HapMap SNPs (Table 2)²⁹. The ancestral alleles at all SNPs were fixed in the YRI and CHB+JPT HapMap panels, yielding significant global differentiation (Table 2). Taken together, these results support the hypothesis of a selective sweep that increased the frequency of CAD, T1D and celiac disease risk alleles in Europeans and geographically nearby populations but not in East Asian or African populations.

DISCUSSION

This study represents, to our knowledge, the first GWA of hematological parameters to be completed in cohorts with large sample sizes. In a two-stage design with 4,627 discovery and 9,316 replication samples, we were able to confirm 22 independent loci as associated with 6 of the 8 traits at the genome-wide significance level. None of the loci selected from the meta-analysis of MCHC and Hb were replicated at genome-wide significance in our study. However, genome-wide significance for Hb was achieved for rs5756506 at locus *TMPRSS6* in the combined analysis (Supplementary Table 4). The regions identified contain several plausible regulators of hematopoiesis in humans (see also Supplementary Table 3 for discussion on likely candidates). Associations with erythrocyte-related traits are dominated by two main effect loci, rs1800562 in *HBSIL-MYB* and the nonsynonymous change rs9402686 in *HFE*. Three loci (*HFE*, *TFR2* and *TMPRSS6*) mapped to genes known to be associated with iron homeostasis. The nonsynonymous C282Y change in *HFE* (rs9402686) is a classic risk allele for hereditary hemochromatosis, but here we show for the first time that it also modifies MCV.

The 12 MPV loci showed similar per-allele effect sizes (Table 1) and jointly explain 8.6% of total genetic variance in MPV after adjusting for age and sex. We identified several key functional categories of genes implicated in the regulation of platelet counts and volume, including transcriptional activation (*WDR66* and *JMJD1C*), intracellular signaling (*PIK3CG*, *ARHGEF3*, *TAOK1* and *SH2B3*), protein transport and endocytosis (*BET1L*, *DNM3* and *EHD3*), cell adhesion (*SIRPA* and *CD226*) and actin-myosin contraction and cell motility (*TPM1*) and apoptosis (*BAK1*). Of these, only a handful of genes encode proteins that had previously known roles in hematopoiesis in humans and mouse knockout models (*PIK3CG-PRKAR2B*, *ARHGEF3*, *JMJD1C*, *CD226*, *BAK1*, *SH2B3-PTPN11* and *SIRPA*). *SIRPA* and *CD226* both encode MK membrane proteins; results from cell biology studies in MK cells are strongly supportive of their candidacy for association to MPV (Supplementary Table 3). The marked overexpression of *DNM3* in MKs compared with other blood cells and the increase in the *TPM1* transcript level with MK polyploidization both support of the putative role of these proteins in MK and platelet biology, but further studies will be required to discern their precise role.

We also detected a greater number of loci for MPV than for red and, particularly, white blood cell traits. Measurements of WBC included all different white cell subtypes, thus adding to the overall noise in the association analysis and lowering power. It is possible that dissecting the WBC measurement into the main types of mononuclear cellular elements (lymphocytes, monocytes and granulocytes) may improve the ability to identify a large number of additional loci. A recent study identified an association of the Arg262Trp nonsynonymous change in the gene *SH2B3* (rs3184504) and eosinophil counts and CAD ($P = 8.6 \times 10^{-8}$)²¹. The same locus was identified in our study as being strongly associated with PLT and CAD.

We extended knowledge of this locus by characterizing the association signal as a common (frequency ~40%) long-range haplotype (1.6 Mb) including the Arg262Trp site, seven intronic SNPs (in *ATXN2*, *C12orf30*, *C12orf51* and *PTPN11*) and two intergenic SNPs. We obtained strong evidence suggesting that the haplotype at 12q24 has arisen from a selective sweep specific to Europeans and nearby populations beginning approximately 3,400 years ago, a period characterized by the expansion of high-density human settlements in this part of the world. The role of this region in T cell-mediated immune response is compatible with the notion of immunity being a strong selective force in human evolution²⁸.

The 12q24 haplotype links risk alleles for T1D, CAD and celiac disease (carried on the derived haplotype) as well as a recently identified association with hypertension³⁰, thus highlighting a remarkable example of disease pleiotropy at this locus. The functional validation of the effect of the Arg262Trp variant in *SH2B3* and other variants on this haplotype will be important to clarify and dissect the underlying causes of such pleiotropy and also to establish whether variation in PLT and/or the Arg262Trp change are causal for CAD or whether they merely reflect a pleiotropic effect due to the persistence of multiple functional variants on the long-range haplotype. *SH2B3* encodes Lnk, an important negative regulator of cell-signaling events originating from cell membrane activatory receptors such as the T-cell receptor and MPL, the receptor for thrombopoietin on MKs and platelets. Lnk-mediated regulation of Stat-5 activation regulates the crosstalk between integrin- and cytokine-mediated signaling³¹. Cells from Lnk-deficient mice show an increased sensitivity to several cytokines and altered activation of the RAS-MAPK pathway in response to IL3 and stem cell factor³². Using homology to mouse protein models, we mapped Arg262Trp to a putative pleckstrin homology domain (Supplementary Note and Supplementary Fig. 2). A possible functional effect could be caused by a charge reversal of this surface-exposed residue, affecting interaction with unidentified downstream signaling molecules. Pleckstrin

homology domains form a structurally conserved family associated with several regulatory pathways through signal transduction or protein ligand recognition³³.

Further functional assessment and in-depth analysis of the 12q24 region will be required to dissect the pleiotropic effects observed at this locus and, in particular, the causality relationship between platelet counts and CAD risk. We note that the region covered by the long-range haplotype contains a number of other candidate genes that may modify platelet phenotypes. The tyrosine-protein phosphatase non-receptor type 11 encoded by *PTPN11* plays a regulatory role in a wide array of cell-signaling events involved in the control of cell functions, such as mitogenic activation, metabolic control, transcription regulation and cell migration. Mutations in *PTPN11* are a cause of the mendelian disorder Noonan syndrome, which is characterized by platelet abnormalities^{34,35} and acute myeloid leukemias^{36,37}. Also in this region, *BRAP* (encoding BRCA1-associated protein) was shown to interact *in vitro* and *in vivo* with p21 (encoded by *CDKN1A*), a regulator of cell cycle progression previously implicated in atherosclerosis³⁸. Notably, a recent study in Japanese individuals has detected an association between common SNPs in *BRAP* and risk of CAD³⁹. Such an effect, however, is not explained by the Arg262Trp variant in *SH2B3*, which is absent in East Asian populations.

An overarching scope of our analysis was to test whether blood cell loci, particularly those for platelets, are risk loci for cardiovascular disease. Apart from the association signal on 12q24, we found no overwhelming evidence for contribution of these loci to the risk of CAD or MI. Increased MPV represents a strong, independent predictor of post-event outcome in CAD^{6,40–42}, and the new loci might contribute to survival and prognosis after a major CAD event. This possibility merits further investigation. Finally, the regions identified provide new targets to study in a range of other related diseases. For example, platelets are proposed as having a role in cancer progression and metastasis, which has largely been attributed to platelet-mediated enhancement of tumor cell survival, extravasation and angiogenesis. It has been proposed that platelet inhibition may slow the rate of tumor progression and metastasis. Further characterization of these loci will improve our understanding of key regulatory mechanisms of hematopoiesis in humans and may also lead to the discovery of new candidate genes that are somatically mutated in premalignant conditions such as essential thrombocytosis and polycythemia vera and in other hematological malignancies.

ONLINE METHODS

Methods and any associated references are available in the online version of the paper at <http://www.nature.com/naturegenetics/>.

Note: Supplementary information is available on the Nature Genetics website.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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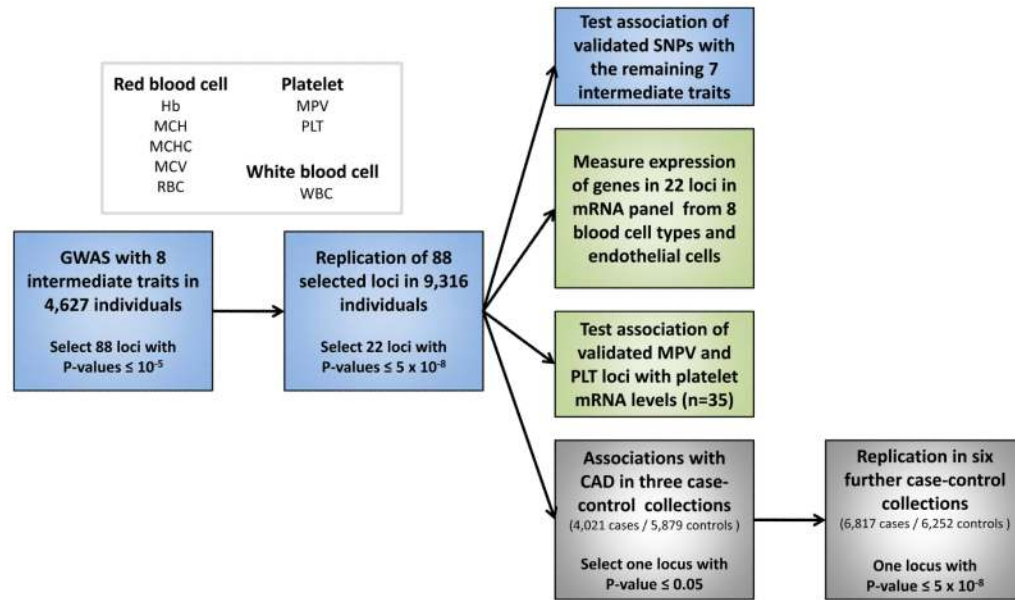


Figure 1.
Summary of the study design.

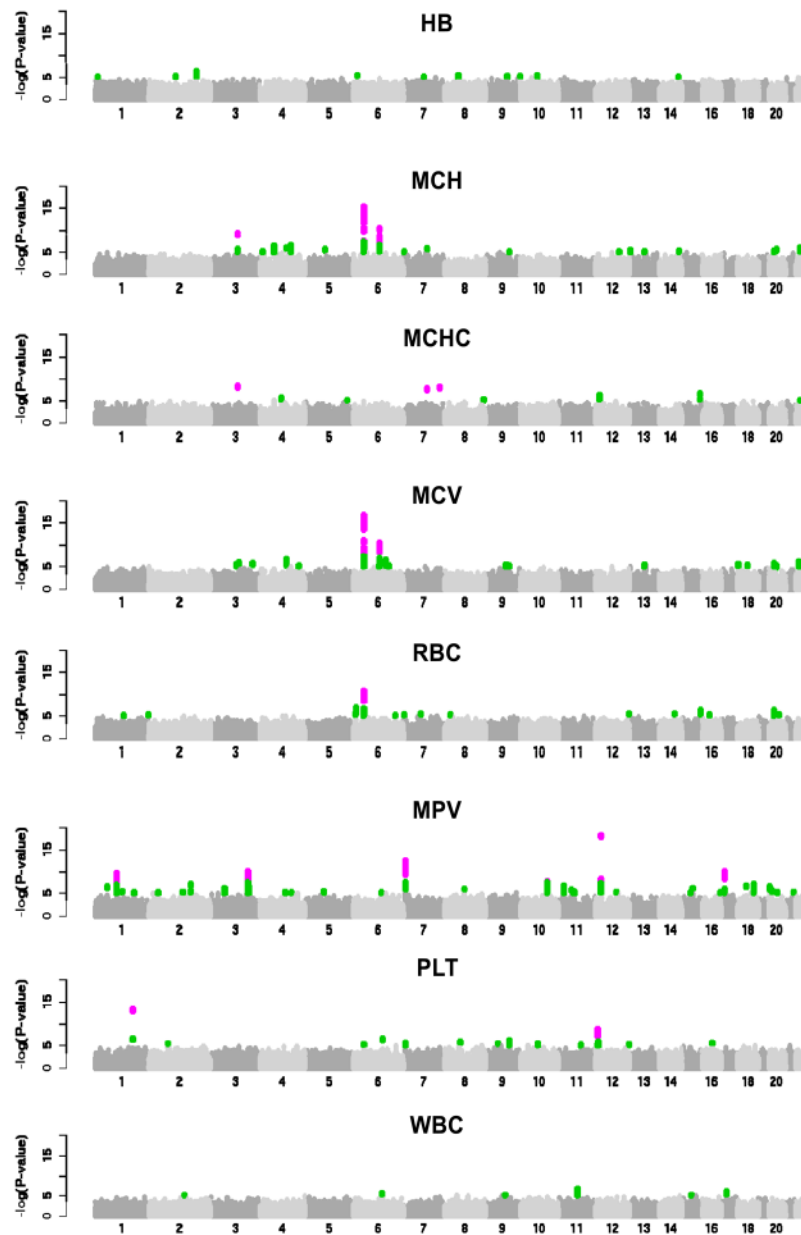


Figure 2. Manhattan plots describing the association of 2.11 M SNPs with eight hematology traits in the three discovery samples (UKBS-CC1, TwinsUK and KORA F3 500K). SNPs with $P \leq 10^{-5}$ are highlighted in green; SNPs exceeding the genome-wide significance threshold of 5×10^{-8} are shown in purple.

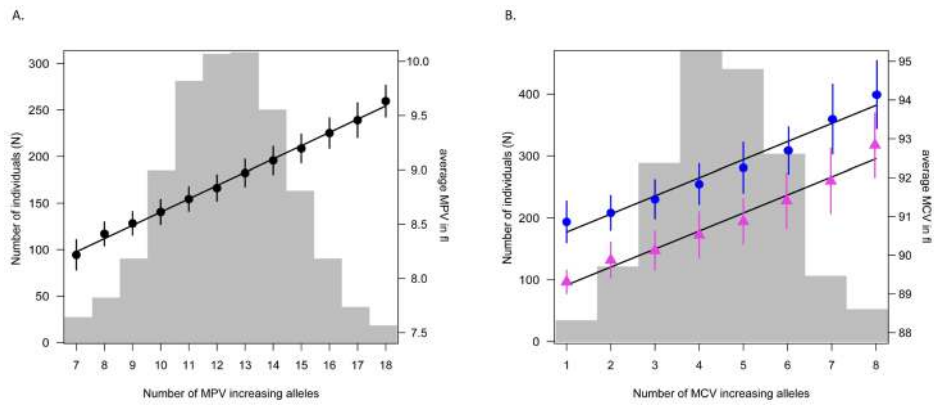
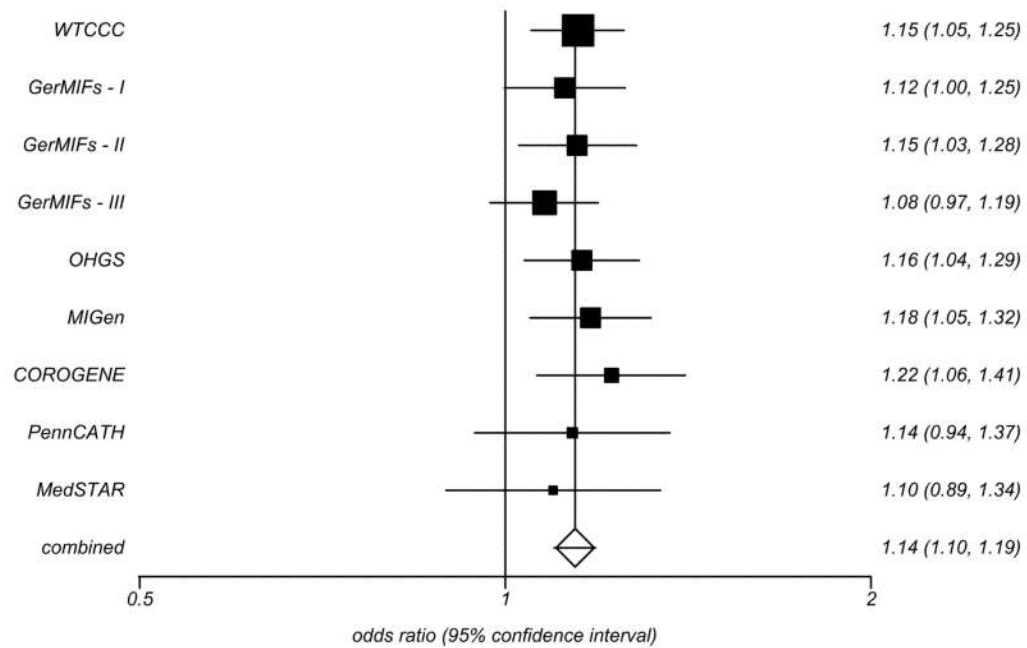


Figure 3.

Multimarker score tests for MPV and MCV. **(a)** MPV scores were calculated from the 12 validated MPV loci and are given for individuals with ≤ 7 , 8 17 and ≥ 18 MPV-increasing alleles. **(b)** MCV scores were calculated from six validated red blood cell loci. MCV multimarker scores were calculated for males and females separately to account for substantial differences among sexes. Gray bars indicate the number of individuals in each score class, dots and triangles indicate the mean MPV and mean MCV levels in each class with bars showing the associated standard errors (blue for males and magenta for females); the lines are the linear regressions through these points. The regression indicates an average increase of MPV of 0.12 fl per copy of MPV-increasing allele, corresponding to a variation of between 8.25 and 9.59 fl for individuals carrying between 7 and 18 copies of MPV-increasing alleles, respectively. The corresponding average increase in MCV was 0.47 fl per allele (range 90.60–93.86 fl for individuals carrying ≤ 1 or ≥ 8 copies of MCV-increasing alleles) in males and 0.47 fl (range 89.23–92.49 fl for the same range of alleles) in females, respectively.

Summary meta-analysis plot [fixed effects]

**Figure 4.**

Association of SNP rs11065987 with CAD. Pooled ORs and 95% CI were calculated in eight case-control studies of European origin under a fixed effects model, as there was no evidence for heterogeneity in associations at this locus. The remaining nine SNPs characterizing this haplotype are described in Supplementary Table 5.

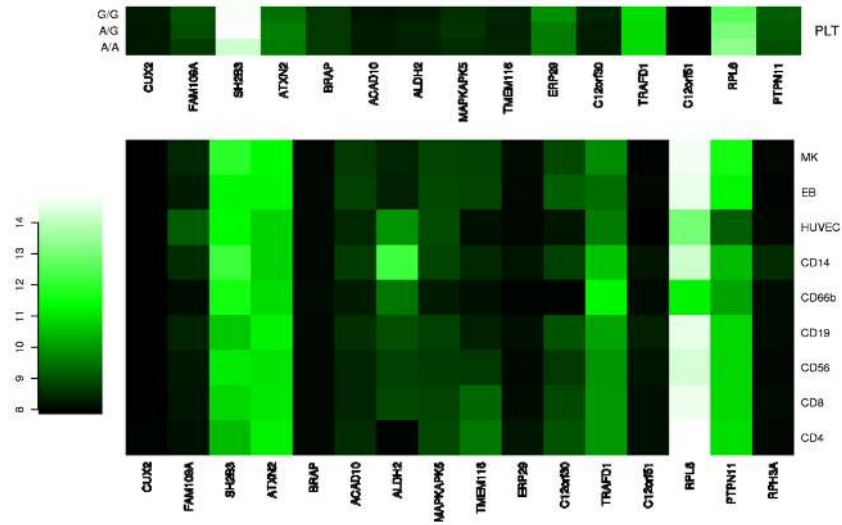


Figure 5. Heatmap of mRNA expression in the 12q24 region. For all genes contained within the 1.6-Mb interval, VST-transformed signal intensities from using Illumina HumanWG-6 (v2) Expression BeadChip expression arrays were median-normalized and values were averaged across biological replicates in stem cell-derived erythroblasts (EBs, $n = 4$), megakaryocytes (MK, $n = 4$), human umbilical vein endothelial cells (HUVECs, $n = 3$), CD4⁺ Th (CD4, $n = 7$) and CD8⁺ Tc lymphocytes (CD8, $n = 7$), CD14⁺ monocytes (CD14, $n = 7$), CD19⁺ B lymphocytes (CD19, $n = 7$), CD56⁺ natural killer cells (CD56, $n = 7$) and CD66b⁺ granulocytes (CD66, $n = 7$). For platelet-associated signals, levels of gene expression in 35 platelet mRNA were averaged based on genotype at the leading or proxy SNP. Signal intensities obtained with platelets were obtained using Illumina HumanWG-6 (v1) Expression BeadChip expression arrays and were normalized independently from the remaining blood cell lines.

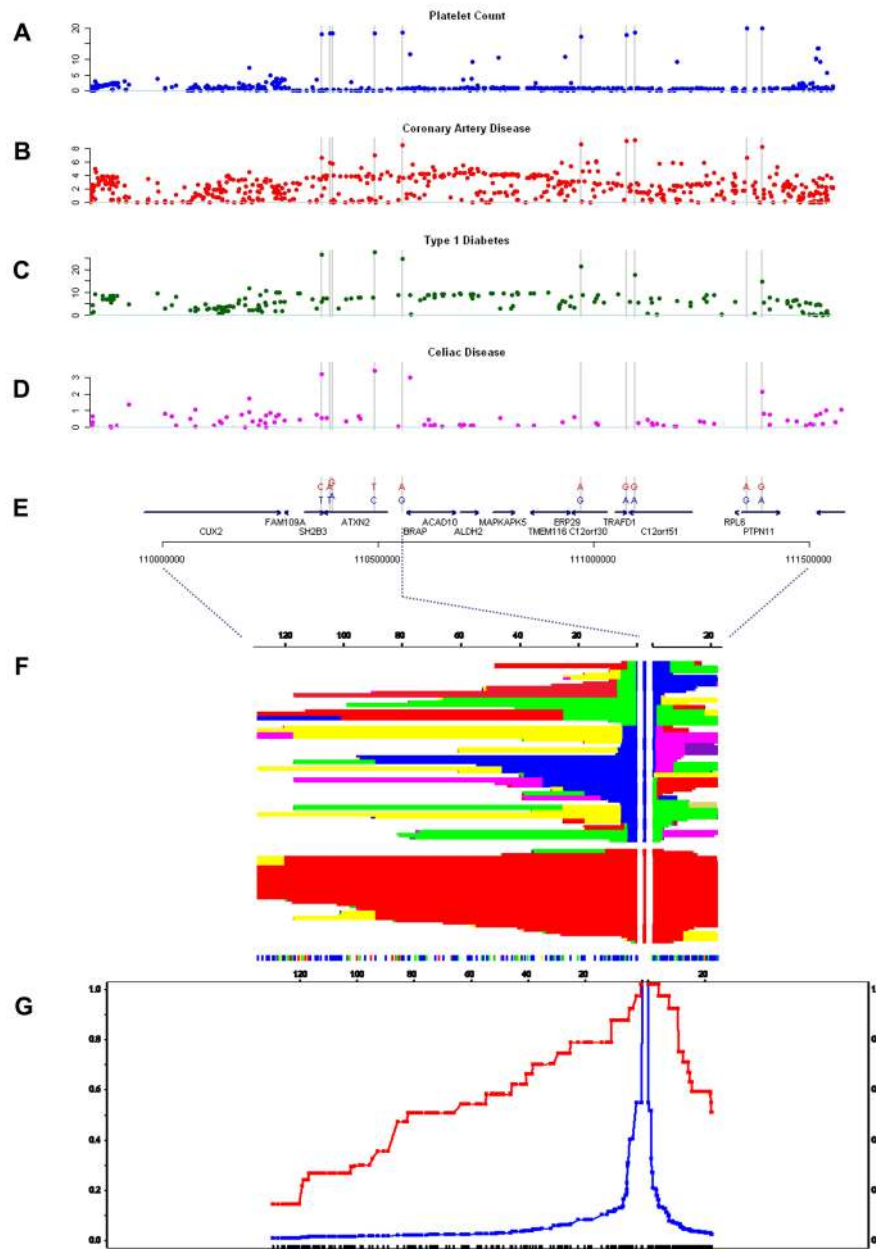


Figure 6. Overview of the 12q24 region. (a–d) The $-\log_{10} P$ value for associations with platelet counts (a), coronary artery disease (b), type 1 diabetes (c) and celiac disease (d), expressed in $-\log_{10}(P$ value), are shown for two consecutive recombination intervals in a 1.6-MB region on chromosome 12 (Build 36 pos 109,896,664–111,516,664). (e) The position of the 10 SNPs forming a high frequency (MAF 40%) haplotype is highlighted by gray bars; this also displays the evolutionarily ancestral (blue) and derived (red) alleles at the 10 SNPs. (f,g) Signatures of positive selection obtained from Haplotter, including a graphical display of haplotypes at different distances from the lead SNP rs11065987 (f) and a plot marking the decay of extended haplotype homozygosity at different distances from SNP rs11065987 (g).

Table 1

22 loci that reached genome-wide significance for association with eight hematological traits

Trait	SNP	Chr (build 36)	Pos (build 36)	Cytoband	Locus	Minor allele	MAF CEU	AI/A2 ^a	Discovery (n = 4,627)			Replication (n = 9,316)			Combined (n = 13,943)			
									Beta (s.e.m.)	P	I ² (%)	Beta (s.e.m.)	P	I ² (%)	Beta (s.e.m.)	P	I ² (%)	
MCH (pg)	rs5756506b	22	35,797,338	22q12.3	<i>TMPRSS6</i>	C	0.35	C/G	0.192 (0.040)	1.2 × 10 ⁻⁶	0	0.111 (0.027)	4.4 × 10 ⁻⁵	0	0.18	0.137 (0.022)	9.5 × 10 ⁻¹⁰	0
	rs11970772	6	42,033,268	6p21.1	<i>BYSL/CCND3</i>	A	0.15	A/T	0.591 (0.117)	4.7 × 10 ⁻⁷	0	0.569 (0.078)	2.7 × 10 ⁻¹³	50	0.51	0.575 (0.065)	7.0 × 10 ⁻¹⁹	0
	rs1800562	6	26,201,120	6p21.3	<i>HFE</i>	A	0.04	A/G	1.319 (0.201)	5.9 × 10 ⁻¹¹	50	1.494 (0.197)	3.1 × 10 ⁻¹⁴	0	0.94	1.408 (0.141)	1.4 × 10 ⁻²³	18
	rs9609565	22	31,197,528	22q12-q13	<i>FBXO7</i>	A	0.25	G/A	0.549 (0.111)	8.2 × 10 ⁻⁷	0	0.301 (0.071)	2.0 × 10 ⁻⁵	0	0.17	0.372 (0.060)	4.3 × 10 ⁻¹⁰	20
MCV (fl)	rs9402686	6	135,469,510	6q23-q24	<i>HBS1L-MYB</i>	A	0.22	A/G	0.909 (0.109)	9.1 × 10 ⁻¹⁷	14	0.777 (0.072)	5.9 × 10 ⁻²⁷	65	1.16	0.818 (0.060)	7.4 × 10 ⁻⁴²	37
	rs7385804	7	100,073,906	7q22	<i>TFR2</i>	C	0.38	C/A	0.008 (0.002)	4.7 × 10 ⁻⁶	0	0.005 (0.001)	1.2 × 10 ⁻⁵	33	0.17	0.006 (0.001)	4.9 × 10 ⁻¹⁰	0
RBC (10¹²/l), log	rs10914144	1	170,216,373	1q24.3	<i>DNM3</i>	T	0.17	C/T	0.016 (0.003)	2.9 × 10 ⁻⁷	48	0.012 (0.002)	7.3 × 10 ⁻⁹	0	0.34	0.013 (0.002)	2.1 × 10 ⁻¹⁴	9
	rs11071720	15	61,129,049	15q22.1	<i>TPM1</i>	T	0.37	T/C	0.013 (0.003)	6.5 × 10 ⁻⁷	27	0.008 (0.003)	3.1 × 10 ⁻³	8	0.18	0.011 (0.002)	1.9 × 10 ⁻⁸	31
	rs11602954	11	192,856	11p15.5	<i>BET1L</i>	A	0.23	G/A	0.014 (0.003)	1.9 × 10 ⁻⁶	0	0.013 (0.002)	1.4 × 10 ⁻⁹	25	0.41	0.013 (0.002)	1.3 × 10 ⁻¹⁴	0
	rs12485738	3	56,840,816	3p21-p13	<i>ARHGEF3</i>	A	0.42	A/G	0.013 (0.002)	1.5 × 10 ⁻⁸	71	0.016 (0.002)	4.5 × 10 ⁻²⁴	0	0.93	0.015 (0.001)	5.5 × 10 ⁻³¹	46
	rs1668873	1	203,502,613	1q32.1	<i>TMC22</i>	A	0.33	G/A	0.015 (0.002)	3.3 × 10 ⁻¹⁰	0	0.011 (0.002)	2.4 × 10 ⁻¹²	27	0.49	0.012 (0.001)	1.4 × 10 ⁻²⁰	24
	rs2138852	17	24,727,475	17q11.2	<i>TAOK1</i>	C	0.44	T/C	0.014 (0.002)	2.5 × 10 ⁻⁹	57	0.018 (0.002)	4.5 × 10 ⁻¹⁵	0	1.21	0.016 (0.002)	1.4 × 10 ⁻²²	34
	rs2393967	10	64,803,162	10q21.2-q21.3	<i>JMJD1C</i>	C	0.37	A/C	0.014 (0.002)	2.3 × 10 ⁻⁸	0	0.015 (0.002)	2.3 × 10 ⁻¹⁴	0	0.68	0.014 (0.002)	3.3 × 10 ⁻²¹	0
	rs342293	7	106,159,455	7q22.3	<i>PIK3CG</i>	G	0.45	G/C	0.017 (0.002)	6.8 × 10 ⁻¹³	22	0.015 (0.002)	2.3 × 10 ⁻²²	69	0.96	0.015 (0.001)	1.6 × 10 ⁻³³	48
	rs6136489	20	1,871,734	20p13	<i>SIRPA</i>	G	0.26	T/G	0.012 (0.002)	1.3 × 10 ⁻⁶	24	0.009 (0.002)	7.6 × 10 ⁻⁶	0	0.25	0.010 (0.002)	7.7 × 10 ⁻¹¹	8
	rs647316	2	31,318,333	2p21	<i>EHD3</i>	A	0.25	A/G	0.013 (0.002)	7.4 × 10 ⁻⁸	63	0.008 (0.002)	2.8 × 10 ⁻⁵	55	0.39	0.010 (0.002)	3.2 × 10 ⁻¹¹	59
MPV (fl), log	rs7961894	12	120,849,966	12q24.31	<i>WDR66</i>	T	0.12	T/C	0.036 (0.004)	8.2 × 10 ⁻¹⁹	0	0.029 (0.003)	1.3 × 10 ⁻²⁷	0	1.39	0.031 (0.002)	2.7 × 10 ⁻⁴⁴	0
	rs893001	18	65,667,825	18q22.3	<i>CD226</i>	A	0.47	C/A	0.013 (0.002)	8.3 × 10 ⁻⁸	0	0.009 (0.002)	1.9 × 10 ⁻⁴	0	0.27	0.011 (0.002)	1.4 × 10 ⁻¹⁰	0
	rs11065987	12	110,556,807	12q24	<i>ATXN2</i>	G	0.34	G/A	7.521 (1.305)	8.3 × 10 ⁻⁹	0	4.118 (0.815)	4.4 × 10 ⁻⁷	0	0.23	5.073 (0.692)	2.2 × 10 ⁻¹³	31
	rs11066301	12	111,355,755	12q24	<i>PTPN11</i>	G	0.35	G/A	7.479 (1.251)	2.3 × 10 ⁻⁹	0	3.467 (0.809)	1.8 × 10 ⁻⁵	0	0.16	4.650 (0.680)	7.7 × 10 ⁻¹²	45
PLT (10⁹/l)	rs210135	6	33,648,670	6p21.3	<i>BAK1</i>	T	0.32	A/T	6.908 (1.342)	2.6 × 10 ⁻⁷	0	4.380 (1.138)	1.2 × 10 ⁻⁴	0	0.19	5.438 (0.868)	3.7 × 10 ⁻¹⁰	0
	rs385893	9	4,753,176	9p24.1-p24.3	<i>AK3</i>	T	0.44	C/T	6.951 (1.389)	5.6 × 10 ⁻⁷	47	5.979 (0.895)	2.4 × 10 ⁻¹¹	24	0.33	6.264 (0.753)	8.5 × 10 ⁻¹⁷	26
	rs17609240	17	35,364,215	17q12	<i>GSDMA/ORMDL3</i>	T	0.26	G/T	0.030 (0.006)	1.2 × 10 ⁻⁶	0	0.015 (0.004)	2.1 × 10 ⁻⁴	11	0.12	0.019 (0.003)	9.4 × 10 ⁻⁹	33

^a AI/A2 aligned to CEU + strand, increaser allele.

^b After replication, this locus was most significant for MCV (Beta = 0.369 (0.056), $P = 3.8 \times 10^{-11}$).

For each locus, the association statistics were calculated using inverse-variance meta-analysis separately in the three discovery (UKBS-CC1, TwinsUK and KORA F3 500K) and three replication samples (KORA F4, SHIP and CBR) and in the combined sample. I^2 (%) measures the percentage of total variation across studies due to heterogeneity. Most of the loci show small to moderate heterogeneity, with only rs647316 displaying substantial heterogeneity ($I^2 = 59\%$).

Table 2

Association with disease and signatures of natural selection at the 10 core SNPs in the 12q24 region

SNP	Gene annotation	Platelet count association			CAD			Natural selection						
		Increaser allele	Beta (s.e.m.) (10 ⁹ /l)	P	Risk allele	OR (95% CI)	P	Ancestral/derived allele	DAF ^c CEU	DAF ^c YRI	DAF ^c CHB	Standardized iHS	Fay and Wu's H ⁺	FST ^d
rs3184504 ^a	<i>SH2B3</i> (Arg262Trp)	T	7.22 (1.28)	1.6 × 10 ⁻⁸	T	1.186 (1.127–1.248)	5.04 × 10 ⁻¹¹	C/T	0.41	0	0	-2.756	-35.656	0.39**
rs4766578 ^a	<i>ATXN2</i> (intron)	T	7.33 (1.28)	1.0 × 10 ⁻⁸	T	1.169 (1.107–1.234)	1.57 × 10 ⁻⁸	A/T	0.42	-	-	-2.761	-37.062	-
rs10774625 ^a	<i>ATXN2</i> (intron)	A	7.33 (1.28)	9.9 × 10 ⁻⁹	A	1.169 (1.107–1.234)	1.66 × 10 ⁻⁸	G/A	0.42	0	0	-2.761	-36.22	0.40**
rs653178 ^a	<i>ATXN2</i> (intron)	C	7.25 (1.27)	1.2 × 10 ⁻⁸	C	1.181 (1.123–1.241)	6.30 × 10 ⁻¹¹	T/C	0.41	0	0	-2.882	-34.185	0.39**
rs11065987	Intergenic	G	7.52 (1.31)	8.3 × 10 ⁻⁹	G	1.177 (1.124–1.231)	2.42 × 10 ⁻¹²	A/G	0.34	0	0	-3.038	-36.295	0.34*
rs17696736 ^b	<i>C12orf30</i> (intron)	G	6.89 (1.24)	3.1 × 10 ⁻⁸	G	1.164 (1.114–1.216)	1.47 × 10 ⁻¹¹	A/G	0.35	0	0	-3.212	-57.263	0.34*
rs17630235	<i>TRAFD1</i> (3' of gene)	A	7.07 (1.25)	1.7 × 10 ⁻⁸	A	1.167 (1.113–1.223)	1.48 × 10 ⁻¹⁰	G/A	0.33	0	0	-3.206	-61.348	0.32*
rs11066188	<i>C12orf51</i> (intron)	A	7.22 (1.25)	8.5 × 10 ⁻⁹	A	1.171 (1.120–1.225)	5.12 × 10 ⁻¹²	G/A	0.32	0.008	0	-3.227	-60.794	0.30*
rs11066301	<i>PTPN11</i> (intron)	G	7.48 (1.25)	2.3 × 10 ⁻⁹	G	1.165 (1.111–1.222)	3.43 × 10 ⁻¹⁰	A/G	0.35	0.008	0	-2.646	-56.342	0.33*
rs11066320	<i>PTPN11</i> (intron)	A	7.48 (1.25)	2.3 × 10 ⁻⁹	A	1.169 (1.117–1.223)	1.33 × 10 ⁻¹¹	G/A	0.35	0	0	-4.341	-59.37	0.34*

^a CAD data not available for WTCCC-CAD; T (derived) allele at rs3184504 increases risk for celiac disease.

^b All cohorts with genotyped calls; G (derived) allele increases risk for T1D.

^c DAF = derived allele frequency.

^d Global *F_{ST}* for the comparison of CEU/YRI/CHB+JPT calculated from HapMap Phase II data. The symbols * and ** indicate SNPs exceeding the 95th (*F_{ST}* = 0.309) and 99th (*F_{ST}* = 0.37) percentiles of the empirical genome-wide distribution for this MAF bin (0.05 0.1 worldwide).

The PLT summary statistics are relative to the discovery sample. The derived and ancestral allele status was obtained from the UCSC annotations. Derived allele frequencies in the three HapMap Phase 2 samples were obtained from the HapMap repository. The natural selection statistics iHS and Fay and Wu's H⁺ for HapMap Phase 2 were obtained from Haploplotter.