

VU Research Portal

Variants in MTNR1B influence fasting glucose levels

Prokopenko, I.; Langenberg, C.; Florez, J.C.; Saxena, R.; Soranzo, N.; Thorleifsson, G.; Loos, R.J.F.; Manning, A.K.; Jackson, A.U.; Aulchenko, Y.S.; Potter, S.C.; Erdos, M.R.; Sanna, S.; Hottenga, J.J.; Wheeler, E.; Kaakinen, M.; Lyssenko, V.; Chen, W.-M.; Ahmadi, K.; Beckmann, J.S.

published in

Nature Genetics
2009

DOI (link to publisher)

[10.1038/ng.290](https://doi.org/10.1038/ng.290)

[Link to publication in VU Research Portal](#)

citation for published version (APA)

Prokopenko, I., Langenberg, C., Florez, J. C., Saxena, R., Soranzo, N., Thorleifsson, G., Loos, R. J. F., Manning, A. K., Jackson, A. U., Aulchenko, Y. S., Potter, S. C., Erdos, M. R., Sanna, S., Hottenga, J. J., Wheeler, E., Kaakinen, M., Lyssenko, V., Chen, W.-M., Ahmadi, K., ... Abecasis, G. R. (2009). Variants in MTNR1B influence fasting glucose levels. *Nature Genetics*, 41(1), 77-81. <https://doi.org/10.1038/ng.290>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

E-mail address:

vuresearchportal.ub@vu.nl

Variants in *MTNR1B* influence fasting glucose levels

Inga Prokopenko^{1,2,64}, Claudia Langenberg^{3,64}, Jose C Florez^{4–6,64}, Richa Saxena^{4,7,64}, Nicole Soranzo^{8,9,64}, Gudmar Thorleifsson¹⁰, Ruth J F Loos³, Alisa K Manning¹¹, Anne U Jackson¹², Yurii Aulchenko¹³, Simon C Potter⁸, Michael R Erdos¹⁴, Serena Sanna¹⁵, Jouke-Jan Hottenga¹⁶, Eleanor Wheeler⁸, Marika Kaakinen¹⁷, Valeriya Lyssenko¹⁸, Wei-Min Chen^{19,20}, Kourosh Ahmadi⁹, Jacques S Beckmann^{21,22}, Richard N Bergman²³, Murielle Bochud²⁴, Lori L Bonnycastle¹⁴, Thomas A Buchanan²⁵, Antonio Cao¹⁵, Alessandra Cervino⁹, Lachlan Coin²⁶, Francis S Collins¹⁴, Laura Crisponi¹⁵, Eco J C de Geus¹⁶, Abbas Dehghan¹³, Panos Deloukas⁸, Alex S F Doney²⁷, Paul Elliott²⁶, Nelson Freimer²⁸, Vesela Gateva¹², Christian Herder²⁹, Albert Hofman¹³, Thomas E Hughes³⁰, Sarah Hunt⁸, Thomas Illig³¹, Michael Inouye⁸, Bo Isomaa³², Toby Johnson^{21,24,33}, Augustine Kong¹⁰, Maria Krestyaninova³⁴, Johanna Kuusisto³⁵, Markku Laakso³⁵, Noha Lim³⁶, Ulf Lindblad^{37,38}, Cecilia M Lindgren², Owen T McCann⁸, Karen L Mohlke³⁹, Andrew D Morris²⁷, Silvia Naitza¹⁵, Marco Orrù¹⁵, Colin N A Palmer⁴⁰, Anneli Pouta^{41,42}, Joshua Randall², Wolfgang Rathmann⁴³, Jouko Saramies⁴⁴, Paul Scheet¹², Laura J Scott¹², Angelo Scuteri⁴⁵, Stephen Sharp³, Eric Sijbrands⁴⁶, Jan H Smit⁴⁷, Kijoung Song³⁶, Valgerdur Steinthorsdottir¹⁰, Heather M Stringham¹², Tiinamaija Tuomi⁴⁸, Jaakko Tuomilehto^{49,50}, André G Uitterlinden⁴⁶, Benjamin F Voight^{4,7}, Dawn Waterworth³⁶, H-Erich Wichmann^{31,51}, Gonneke Willemssen¹⁶, Jacqueline C M Witteman¹³, Xin Yuan³⁶, Jing Hua Zhao³, Eleftheria Zeggini², David Schlessinger⁵², Manjinder Sandhu^{3,53}, Dorret I Boomsma¹⁶, Manuela Uda¹⁵, Tim D Spector⁹, Brenda WJH Penninx^{53–55}, David Altshuler^{4–7}, Peter Vollenweider⁵⁶, Marjo Riitta Jarvelin^{17,26,42}, Edward Lakatta⁵², Gerard Waeber⁵⁶, Caroline S Fox^{57,58}, Leena Peltonen^{8,59,60}, Leif C Groop¹⁸, Vincent Mooser³⁶, L Adrienne Cupples¹¹, Unnur Thorsteinsdottir^{10,61}, Michael Boehnke¹², Inês Barroso⁸, Cornelia Van Duijn¹³, Josée Dupuis¹¹, Richard M Watanabe^{23,62}, Kari Stefansson^{10,61}, Mark I McCarthy^{1,2}, Nicholas J Wareham³, James B Meigs^{5,63} & Gonçalo R Abecasis¹²

To identify previously unknown genetic loci associated with fasting glucose concentrations, we examined the leading association signals in ten genome-wide association scans involving a total of 36,610 individuals of European descent. Variants in the gene encoding melatonin receptor 1B (*MTNR1B*) were consistently associated with fasting glucose across all ten studies. The strongest signal was observed at rs10830963, where each G allele (frequency 0.30 in HapMap CEU) was associated with an increase of 0.07 (95% CI = 0.06–0.08) mmol/l in fasting glucose levels ($P = 3.2 \times 10^{-50}$) and reduced beta-cell function as measured by homeostasis model assessment (HOMA-B, $P = 1.1 \times 10^{-15}$). The same allele was associated with an increased risk of type 2 diabetes (odds ratio = 1.09 (1.05–1.12), per G allele $P = 3.3 \times 10^{-7}$) in a meta-analysis of 13 case-control studies totaling 18,236 cases and 64,453 controls. Our analyses also confirm previous associations of fasting glucose with variants at the *G6PC2* (rs560887, $P = 1.1 \times 10^{-57}$) and *GCK* (rs4607517, $P = 1.0 \times 10^{-25}$) loci.

Blood and plasma fasting glucose levels are tightly regulated within a narrow physiologic range by a feedback mechanism that targets a particular fasting glucose set point for each individual^{1,2}. Disruption of normal glucose homeostasis and substantial elevations of fasting glucose are hallmarks of type 2 diabetes (T2D) and typically result from sustained reduction in pancreatic beta-cell function and insulin secretion.

However, even within healthy, nondiabetic populations there is substantial variation in fasting glucose levels. Approximately one-third of this variation is genetic³, but little of this heritability has been explained. There is growing evidence to suggest that common variants contributing to variation in fasting glucose are largely distinct from those associated with major disruptions of beta-cell function that predispose to T2D. Common sequence variants in the *GCK* (glucokinase) promoter^{4–6}, and around genes encoding the islet-specific glucose-6-phosphatase (*G6PC2*)^{5,6} and the glucokinase regulatory protein (*GCKR*)^{7–9}, have each been associated with individual variation in fasting glucose levels, but have, at best, weak effects on T2D

*A full list of author affiliations appears at the end of the paper.

Received 9 June; accepted 14 October; published online 7 December 2008; doi:10.1038/ng.290

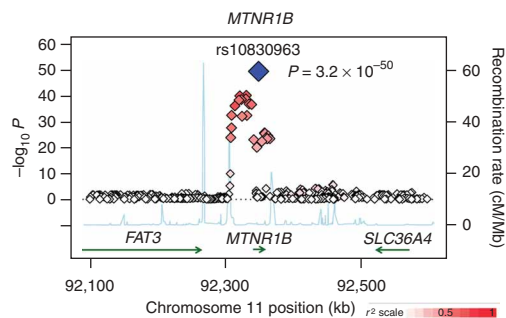


Figure 1 Regional plot of fasting glucose association results for the *MTNR1B* locus across ten MAGIC GWAS. Meta-analysis $-\log_{10} P$ values are plotted as a function of genomic position (NCBI build 35). The SNP with the strongest signal (rs10830963) is denoted by a blue diamond. Estimated recombination rates (from HapMap) are plotted to reflect the local linkage disequilibrium structure around associated SNPs and proxies (according to a white-to-red scale from $r^2 = 0$ to $r^2 = 1$ and based on pairwise r^2 values from HapMap CEU). Gene annotations were taken from the University of California Santa Cruz genome browser.

risk^{8,10}. Furthermore, although there are now over 15 genetic loci strongly associated with the risk of T2D^{7,10–14}, none shows compelling evidence for association with fasting glucose in the two genome-wide association scans (GWAS) so far reported^{5,6}.

MAGIC (the Meta-Analyses of Glucose and Insulin-related traits Consortium) represents a collaborative effort to combine data from multiple GWAS to identify additional loci that affect glycemic and metabolic traits. Our genetic studies of fasting glucose levels were originally organized as four distinct consortia: (i) European Network for Genetic and Genomic Epidemiology (ENGAGE), combining data from deCODE, Northern Finland Birth Cohort 1966 (NFBC1966), Netherlands Twins Register/Netherlands Study of Depression and Anxiety (NTR/NESDA) and the Rotterdam Study; (ii) Genetics of Energy Metabolism (GEM), a meta-analysis of the Lausanne (CoLaus) and TwinsUK scans; (iii) DFS, involving the Diabetes Genetics Initiative (DGI), Finland-United States Investigation of NIDDM Genetics (FUSION) and SardiNIA scans; and (iv) the Framingham Heart Study (FHS). Details of the ten component studies ($n = 1,233$ – $6,479$) are provided in **Supplementary Table 1** online.

As a prelude to more extensive data-sharing, the four consortia initially exchanged the identities of between 10 and 20 SNPs prominently associated with fasting glucose in their individual, interim, meta-analyses ($n = 6,479$ – $12,389$; **Supplementary Table 2** online). Comparison of these signals revealed three loci with consistent effects on fasting glucose detected in multiple studies. Two of these represented the previously reported signals in *G6PC2* and *GCK*. In addition, all four groups independently generated evidence for an association between fasting glucose and SNPs around the *MTNR1B* (melatonin receptor 1B) locus (ENGAGE: rs1387153, $P = 2.2 \times 10^{-17}$; GEM: rs10830963, $P = 7.4 \times 10^{-11}$; DFS: rs10830963, $P = 2.5 \times 10^{-7}$; FHS: rs11020107, $P = 5.8 \times 10^{-4}$, for the most strongly associated SNP exchanged from each analysis). The association signals at all three loci were confirmed on formal meta-analysis including results from all ten studies, after exclusion of individuals with known diabetes (rs560887 (*G6PC2*), $P = 1.1 \times 10^{-57}$; rs4607517 (*GCK*), $P = 1.0 \times 10^{-25}$; rs10830963 (*MTNR1B*), $P = 3.2 \times 10^{-50}$; **Table 1**, **Fig. 1**, **Supplementary Fig. 1**, **Supplementary Table 3** and **Supplementary Methods** online). Subsequent efforts to harmonize additional aspects of data analysis strategies (including the additional

exclusion, where necessary, of individuals with fasting glucose measures ≥ 7 mmol/l) had only a marginal impact on estimates of significance and effect size (**Supplementary Table 4** online).

We attempted to refine the location of the *MTNR1B* association signal by extending the meta-analysis to all SNPs (genotyped and imputed from the HapMap) within the 1-Mb region flanking the gene ($n = 35,812$; 981 SNPs). In all, 30 genotyped and imputed SNPs showed compelling evidence for association with fasting glucose ($P < 10^{-8}$). The strongest signal was detected at rs10830963: the minor (G) allele (frequency 0.30 in HapMap CEU¹⁵) at this SNP was associated with a per-allele increase of 0.07 (95% CI = 0.06–0.08) mmol/l in fasting glucose ($P = 3.2 \times 10^{-50}$). Consistent evidence for association at rs10830963 was observed in all ten component GWAS, irrespective of whether this SNP was genotyped or imputed, and of the genotyping platform (**Table 1** and **Supplementary Table 1**). Repeat meta-analysis within the region after conditioning on rs10830963 revealed no additional independent signals of association (**Supplementary Note** online).

The strength of the association between rs10830963 and fasting glucose was unchanged after adjustment for body mass index (**Supplementary Table 4**). Analyses of fasting insulin levels as well as indices of beta-cell function (HOMA-B) and insulin sensitivity (HOMA-IR) estimated by the homeostasis model assessment¹⁶ were possible in $\sim 24,000$ participants from the ten studies. These established that the glucose-raising allele at rs10830963 was associated with reduced beta-cell function ($P = 1.1 \times 10^{-15}$), with no appreciable effect on fasting insulin or insulin sensitivity (**Supplementary Table 5** and **Supplementary Note** online).

To determine the impact of variants within *MTNR1B* on T2D risk, we carried out a large-scale meta-analysis of 13 T2D case-control samples (18,236 T2D cases, 64,453 controls; corresponding to an effective sample size of 21,179 unrelated cases and 21,179 unrelated controls). We combined data from the deCODE¹³, Rotterdam¹⁷, KORA¹⁸, FUSION stage 2 (ref. 11) and METSIM¹⁰ studies and from several case-control samples from the UK¹⁰ with publicly available data from the DIAGRAM consortium (which itself aggregates GWA data from the WTCCC, DGI and FUSION scans)¹⁰ (**Supplementary Note**). We found strong evidence that the minor G allele of rs10830963 was associated with increased risk of T2D (odds ratio = 1.09 (1.05–1.12), $P = 3.3 \times 10^{-7}$; **Fig. 2** and **Supplementary Table 6** online). The possibility that the fasting glucose association might

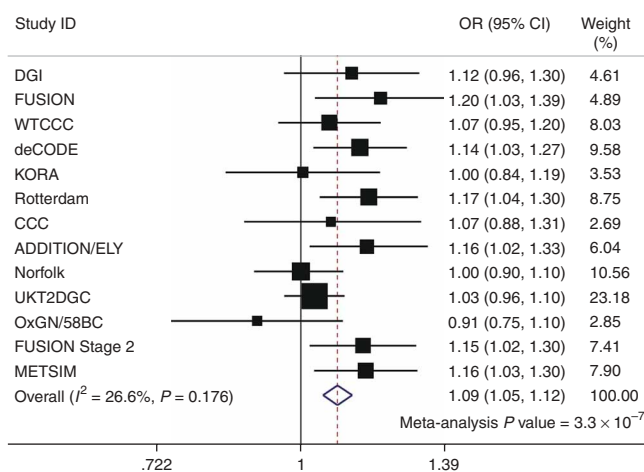


Figure 2 Association of rs10830963 with type 2 diabetes (T2D) in 13 case-control studies.

Table 1 Association of rs10830963 (*MTNR1B*) with fasting glucose levels in ten studies within MAGIC and meta-analysis of best SNPs across all ten studies for three loci associated with fasting glucose (*MTNR1B*, *G6PC2* and *GCK*)

Study sample	N	G allele frequency	Mean mmol/l fasting glucose ^a per genotype (s.d.)			Per-allele effect, mmol/l (s.e.m.)	P value
			CC	CG	GG		
CoLaus	5,000	0.32	5.36 (0.71)	5.46 (0.80)	5.54 (0.81)	0.094 (0.016)	1.9 × 10 ⁻⁹
deCODE	6,240	0.27	5.29 (0.71)	5.39 (0.71)	5.44 (0.71)	0.086 (0.016)	9.2 × 10 ⁻⁸
DGI	1,455	0.31	5.29 (0.54)	5.32 (0.53)	5.39 (0.60)	0.042 (0.022)	0.054
Framingham ^b	6,479	0.28	5.16 (0.48)	5.21 (0.48)	5.26 (0.46)	0.050 (0.012)	2.2 × 10 ⁻¹³
FUSION	1,233	0.33	5.28 (0.49)	5.33 (0.47)	5.40 (0.44)	0.057 (0.016)	5.8 × 10 ⁻⁴
NFBC1966	4,245	0.34	5.63 (0.46)	5.70 (0.49)	5.80 (0.46)	0.079 (0.012)	1.7 × 10 ⁻¹¹
NTR/NESDA	3,166	0.27	5.22 (0.64)	5.26 (0.62)	5.38 (0.63)	0.062 (0.019)	1.2 × 10 ⁻³
Rotterdam	2,058	0.28	5.58 (0.81)	5.75 (0.91)	5.83 (1.03)	0.145 (0.029)	7.9 × 10 ⁻⁷
Sardinia	4,108	0.20	5.62 (0.89)	5.68 (0.89)	5.76 (0.89)	0.070 (0.019)	3.2 × 10 ⁻⁴
TwinsUK ^c	1,828	0.30	4.58 (0.65)	4.67 (0.50)	4.74 (0.57)	0.084 (0.032)	7.9 × 10 ⁻³
rs10830963 (<i>MTNR1B</i>)					Meta-analysis	0.072 (0.005)	3.2 × 10 ⁻⁵⁰
rs560887 (<i>G6PC2</i>)					Meta-analysis	0.064 (0.004)	1.1 × 10 ⁻⁵⁷
rs4607517 (<i>GCK</i>)					Meta-analysis	0.062 (0.007)	1.0 × 10 ⁻²⁵

Fasting glucose levels (mmol/l) are reported untransformed and unadjusted for covariates. Effect of the risk allele and s.e.m. were calculated using untransformed fasting glucose values. P values are reported for the additive genetic model with study-specific transformation of fasting glucose values, adjusted for sex and age.

^aFasting glucose levels in NFBC1966 and SardiNIA were measured in whole blood; in other samples measures were conducted on plasma samples. For these two studies, values in the table are corrected to plasma fasting glucose using a correction factor of 1.13. ^bIn Framingham study, mean fasting glucose values for the imputed SNPs are reported for proxies: rs560887 (proxy rs573225, $r^2 = 0.96$); rs4607517 (proxy rs1799884, $r^2 = 1$); rs10830963 (proxy rs7936247, $r^2 = 0.59$). ^cIn the TwinsUK study, mean fasting glucose values per genotype are estimated for a subset of unrelated individuals only.

reflect the inclusion within the cross-sectional study samples of subjects with undiagnosed T2D can be discounted given that exclusion of those with either known diabetes, or a fasting glucose ≥ 7 mmol/l had little impact on the strength of the association signal (Table 1 and Supplementary Table 4). Although the association with T2D does not, despite large-scale replication efforts, reach the 5×10^{-8} threshold consistent with 'genome-wide significance'¹⁵, it seems highly probable, given the strong impact of this variant on beta-cell function (Supplementary Table 5), that this is a genuine effect.

The analyses we performed interrogate only a fraction of common sequence variants in a given region—it is likely that the causal variant for this locus is yet to be identified. The SNP with the strongest statistical evidence so far, rs10830963, maps within the single 11.5-kb intron of *MTNR1B* but does not seem to disrupt consensus transcription factor binding or cryptic alternative splice sites. The association signal is bounded by recombination hot spots defining a ~ 60 -kb interval within which all our strongly associated SNPs lie and the causal variant is likely to reside. This interval contains the entire coding region of *MTNR1B*. The only other nearby genes (the coding regions of which lie well outside this 60-kb region) are *SLC36A4* and *FAT3*, neither of which are compelling candidates. *SLC36A4* encodes a proton/amino acid transmembrane transporter moderately similar to *Rattus norvegicus* lysosomal amino acid transporter 1, and *FAT3* encodes a cadherin family member which is the human homolog of the *Drosophila melanogaster* FAT tumor suppressor gene. Ultimately, detailed fine mapping and functional analyses will be required to define the causal allele(s) and to confirm that this effect is mediated through altered function or expression of *MTNR1B*.

The size of the MAGIC dataset also allowed us to examine the *G6PC2* and *GCK* regions in greater detail than had previously been possible. In the *G6PC2* region, rs560887, within intron 3 of the gene, remained the strongest signal whether or not imputed data were included ($P = 1.1 \times 10^{-57}$ across all ten studies; Supplementary Fig. 1 online). This is the same SNP reported in one recent paper⁵ and is in substantial linkage disequilibrium (LD; $r^2 = 0.72$ in HapMap CEU) with the lead SNP (rs563694) identified in another⁶. In the *GCK*

region, rs4607517, which lies 6.6-kb upstream of the gene, was the most strongly associated SNP ($P = 1.0 \times 10^{-25}$; Supplementary Fig. 1 and Table 1). This SNP is also in strong LD ($r^2 = 1$ in HapMap CEU) with the *GCK* promoter SNP (rs1799884) that was featured in previous reports⁴. Repeat meta-analysis after conditioning on the respective lead SNPs revealed no additional independent association signals at either locus (Supplementary Note).

As with the variant in *MTNR1B*, the magnitude of the fasting glucose associations for both these signals was unchanged after adjustment for BMI (Supplementary Table 4). Glucose-raising alleles at *GCK* and *G6PC2* were associated with reduced beta-cell function (rs4607517[A], $P = 9.8 \times 10^{-6}$; rs560887[C], $P = 1.2 \times 10^{-26}$; Supplementary Table 5 and Supplementary Note). However, in line with previous reports^{4,9}, neither signal was strongly associated with T2D in the large-scale meta-analysis: in fact, the glucose-raising allele at *G6PC2* was weakly associated with reduced T2D risk (rs4607517[A], per-allele OR = 1.05 (1.00–1.10), $P = 0.031$; rs560887[C], 0.93 (0.89–0.97), $P = 0.0017$; Supplementary Table 6).

We found no influence of the noncoding lead SNPs rs10830963, rs560887 or rs4607517 on gene expression of *MTNR1B*, *SLC36A4*, *FAT3*, *G6PC2* or *GCK* in genome-wide expression QTL datasets from lymphocyte-derived cell lines^{19,20}, cerebral cortex²¹ or liver²², and no evidence for epistatic effects among the three lead SNPs was observed (P for two-way interactions > 0.19 in each of the seven studies including only unrelated individuals; interactions were not examined in the other three studies).

MTNR1B encodes one of two known human melatonin receptors²³. Although this is the first study to implicate genetic variation in *MTNR1B* in the regulation of fasting glucose levels and predisposition to T2D, this relationship is biologically credible. As well as being highly expressed in the brain, retina and elsewhere²⁴, *MTNR1B* is transcribed in human islets and rodent insulinoma cell lines²⁵, and the translated receptor is thought to mediate the inhibitory effect of melatonin on insulin secretion²⁶. Melatonin release is characterized by marked circadian variability and these inhibitory effects on insulin secretion may contribute to the entrainment of circadian patterns of insulin

release²⁷. There is substantial evidence in human and rodent studies linking disturbances of circadian rhythmicity to metabolic conditions including diabetes^{28,29}, and overexpression of melatonin receptors has been observed in islets from individuals with T2D as compared to nondiabetic controls³⁰. Taken together, these findings suggest that the association with raised fasting glucose and T2D may be driven by variants that augment expression and/or activity of islet melatonin receptors.

Our findings bring the number of common variant loci influencing fasting glucose levels to four, three of which were detected in the present study. Variants in *GCKR* have a smaller effect size than the others^{7,9}, and the present study design (based on exchange of a limited number of prominent signals between component groups) was not well-powered to detect these. However, subsequent meta-analysis of *GCKR* variants across all ten study samples confirms the association with fasting glucose (rs780094, $P = 8.5 \times 10^{-9}$; **Supplementary Table 4**). The total variance in fasting glucose now attributable to these four signals is 1.5%, indicating that additional loci remain to be found³. In comparison with *GCK* and *G6PC2*, variants in *MTNR1B* seem to have a more marked effect on risk of T2D, the effect size being comparable in magnitude (OR = 1.09 (1.05–1.12)) to several other T2D-susceptibility genes recently identified in GWAS¹⁰. Thus, although the physiological regulation of fasting glucose set point and the pathological decline in beta-cell function that characterizes common forms of T2D generally seem to involve different processes, the *MTNR1B* finding suggests that this is not always the case. Not only can the study of diabetes-related quantitative traits provide an important path to the identification of additional T2D susceptibility loci, but there may also be opportunities for useful therapeutic overlap.

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

ACKNOWLEDGMENTS

The authors would like to thank the many colleagues who contributed to collection and phenotypic characterization of the clinical samples, as well as genotyping and analysis of the GWA data. They would also like to acknowledge those who agreed to participate in these studies. Major funding for the work described in this paper comes from Academy of Finland (124243); the Administration of Lanusei, Ilbono, Arzana and Elini (Sardinia, Italy); American Diabetes Association (1-05-RA-140); the Center for Inherited Disease Research; Clinical Research Institute (HUCH); Diabetes UK; the European Bioinformatics Institute; the European Commission (contracts LSHM-CT-2006-037197, LSHM-CT-2003-503041, QLK6-CT-2002-02629, QL6-CT-2002-01254, HEALTH-F4-2007-201413, LSHG-CT-2004-512066, QLRT-2001-01254, LSHG-CT-2004-518153); the Faculty of Biology and Medicine of Lausanne; Finnish Diabetes Research Foundation; Folkhalsan Research Foundation; Foundation of the NIH (GAIN initiative); German Federal Ministry of Education and Research; German Federal Ministry of Health and Social Security; German National Genome Research Network; GlaxoSmithKline; GSF-National Research Center for Environment and Health; LMUinnovativ; Ministry of Science and Research of the State North-Rhine Westphalia; Municipality of Rotterdam; US National Institutes of Health (HG-02651, HL-084729, HL-087679, HC-25195, N02-HL-6-4278, DK-078616, DK-080140, DK-065978, RR-163736, MH059160, DK069922, DA-021519, DK-062370, DK-072193, US National Human Genome Research Institute intramural project HG-000024; and the Intramural Program of the National Institute on Aging); the UK National Institute for Health Research (Oxford Biomedical Research Centre and Guys and St. Thomas' Biomedical Research Centre); the Netherlands Ministry of Education, Culture and Science; the Netherlands Ministry of Health, Welfare and Sports; Novartis; NWO (904-61-090, 904-61-193, 480-04-004, 400-05-717); NWOGenomics; NWOInvestments; Research Institute for Diseases in the Elderly (RIDE); Sigrid Juselius Foundation; Spinozapremie; Swedish Research Council (349-2006-237); UK Medical Research Council (G0500539, G0000649, G016121); UK National Health Services Research and Development; the Wellcome Trust (including intramural support for the Wellcome Trust Sanger Institute, GR069224, Strategic Awards 076113 and 083948, Biomedical Collections Grant GR072960); and ZonMw (10-000-1002). A full list of acknowledgments is provided in the **Supplementary Note**.

AUTHOR CONTRIBUTIONS

Project management: **DFS**: R.N.B., A. Cao, F.S.C., K.L.M., J.T., D.S., M.U., E.L., L.C.G., M. Boehnke, G.R.A.; **ENGAGE**: P.E., A.H., J.H.S., H.-E.W., G. Willemsen, D.I.B., B.W.J.H.P., M.R.J., L.P., U.T., C.v.D., K. Stefansson, M.I.M.; **FHS**: J.D., J.B.M.; **GEM**: T.D.S., I.B., N.J.W.

Study design: **DFS**: R.S., V.L., R.N.B., T.A.B., A. Cao, F.S.C., K.L.M., L.J.S., J.T., D.S., M.U., E.L., M. Boehnke, R.M.W., G.R.A.; **ENGAGE**: L.P., A.H., U.T., C.v.D., K. Stefansson, M.I.M.; **FHS**: J.D., J.C.F., J.B.M.; **GEM**: C.L., N.S., R.J.F.L., J.S.B., M. Bochud, D.W., M.S., T.D.S., P.V., G. Waeber, V.M., I.B., N.J.W.

Genome-wide association sampling and genotyping: **DFS**: M.R.E., L.L.B., A. Cao, L. Crispini, T.E.H., B.I., U.L., S.N., M.O., A.S., H.M.S., T.T., J.T., M.U., D.A., L.C.G.; **ENGAGE**: P.E., N.F., A.P., E.S., V.S., A.G.U., J.C.M.W., D.I.B., M.R.J., L.P., U.T., C.v.D., K. Stefansson, M.I.M.; **FHS**: C.S.F., L.A.C., J.D., J.B.M.; **GEM**: K.A., A. Cervino, P.D., M.I., O.T.M.

Statistical analysis and informatics: **DFS**: R.S., A.U.J., S. Sanna, W.-M.C., V.G., P.S., B.F.V., R.M.W.; **ENGAGE**: I.P., G.T., Y.A., J.-J.H., M. Kaakinen, L. Coin, E.J.C.d.G., A.D., C.H., A.K., M. Krestyaninova, C.M.L., J.R., V.S., E.Z., C.v.D.; **FHS**: A.K.M., J.D.; **GEM**: C.L., N.S., S.C.P., E.W., S.H., T.J., N.L., S. Sharp, K. Song, X.Y., J.H.Z.

Replication sampling and genotyping: A.S.F.D., A.H., T.I., M.L., A.D.M., C.N.A.P., W.R., J.S., H.E.W.

MAGIC management committee: I.P., C.L., J.C.F., R.S., N.S., G.T., R.J.F.L., A.U.J., Y.A., E.W., V.L., C.M.L., D.W., D.S., M.S., P.V., G. Waeber, L.C.G., V.M., U.T., M. Boehnke, I.B., J.D., R.M.W., M.I.M., N.J.W., J.B.M., G.R.A.

Writing team: I.P., C.L., J.C.F., R.S., N.S., G.T., M. Boehnke, I.B., C.v.D., J.D., R.M.W., K. Stefansson, M.I.M., N.J.W., J.B.M., G.R.A.

COMPETING INTERESTS STATEMENT

The authors declare competing financial interests: details accompany the full-text HTML version of the paper at <http://www.nature.com/naturegenetics/>.

Published online at <http://www.nature.com/naturegenetics/>

Reprints and permissions information is available online at <http://npg.nature.com/reprintsandpermissions/>

- Xiang, A.H. *et al.* Coordinate changes in plasma glucose and pancreatic beta-cell function in Latino women at high risk for type 2 diabetes. *Diabetes* **55**, 1074–1079 (2006).
- Mason, C.C., Hanson, R.L. & Knowler, W.C. Progression to type 2 diabetes characterized by moderate then rapid glucose increases. *Diabetes* **56**, 2054–2061 (2007).
- Watanabe, R.M. *et al.* Familiality of quantitative metabolic traits in Finnish families with non-insulin-dependent diabetes mellitus. Finland-United States Investigation of NIDDM Genetics (FUSION) Study investigators. *Hum. Hered.* **49**, 159–168 (1999).
- Weedon, M.N. *et al.* A common haplotype of the glucokinase gene alters fasting glucose and birth weight: association in six studies and population-genetics analyses. *Am. J. Hum. Genet.* **79**, 991–1001 (2006).
- Bouatia-Najji, N. *et al.* A polymorphism within the *G6PC2* gene is associated with fasting plasma glucose levels. *Science* **320**, 1085–1088 (2008).
- Chen, W.M. *et al.* Variations in the *G6PC2/ABCB11* genomic region are associated with fasting glucose levels. *J. Clin. Invest.* **118**, 2620–2628 (2008).
- Saxena, R. *et al.* Genome-wide association analysis identifies loci for type 2 diabetes and triglyceride levels. *Science* **316**, 1331–1336 (2007).
- Vaxillaire, M. *et al.* Impact of common type 2 diabetes risk polymorphisms in the DESIR prospective study. *Diabetes* **57**, 244–254 (2008).
- Orho-Melander, M. *et al.* A common missense variant in the glucokinase regulatory protein gene (*GCKR*) is associated with increased plasma triglyceride and C-reactive protein but lower fasting glucose concentrations. *Diabetes* **57**, 3112–3121 (2008).
- Zeggini, E. *et al.* Meta-analysis of genome-wide association data and large-scale replication identifies additional susceptibility loci for type 2 diabetes. *Nat. Genet.* **40**, 638–645 (2008).
- Scott, L.J. *et al.* A genome-wide association study of type 2 diabetes in Finns detects multiple susceptibility variants. *Science* **316**, 1341–1345 (2007).
- Sladek, R. *et al.* A genome-wide association study identifies novel risk loci for type 2 diabetes. *Nature* **445**, 881–885 (2007).
- Steinthorsdottir, V. *et al.* A variant in *CDKAL1* influences insulin response and risk of type 2 diabetes. *Nat. Genet.* **39**, 770–775 (2007).
- Zeggini, E. *et al.* Replication of genome-wide association signals in UK samples reveals risk loci for type 2 diabetes. *Science* **316**, 1336–1341 (2007).

15. The International HapMap Consortium. A haplotype map of the human genome. *Nature* **437**, 1299–1320 (2005).
16. Matthews, D.R. *et al.* Homeostasis model assessment: insulin resistance and beta-cell function from fasting plasma glucose and insulin concentrations in man. *Diabetologia* **28**, 412–419 (1985).
17. Hofman, A. *et al.* The Rotterdam Study: objectives and design update. *Eur. J. Epidemiol.* **22**, 819–829 (2007).
18. Herder, C. *et al.* Variants of the *PPARG*, *IGF2BP2*, *CDKAL1*, *HHEX*, and *TCF7L2* genes confer risk of type 2 diabetes independently of BMI in the German KORA Studies. *Horm. Metab. Res.* **40**, 722–726 (2008).
19. Dixon, A.L. *et al.* A genome-wide association study of global gene expression. *Nat. Genet.* **39**, 1202–1207 (2007).
20. Stranger, B.E. *et al.* Population genomics of human gene expression. *Nat. Genet.* **39**, 1217–1224 (2007).
21. Myers, A.J. *et al.* A survey of genetic human cortical gene expression. *Nat. Genet.* **39**, 1494–1499 (2007).
22. Schadt, E.E. *et al.* Mapping the genetic architecture of gene expression in human liver. *PLoS Biol.* **6**, e107 (2008).
23. Reppert, S.M. *et al.* Molecular characterization of a second melatonin receptor expressed in human retina and brain: the Mel1b melatonin receptor. *Proc. Natl. Acad. Sci. USA* **92**, 8734–8738 (1995).
24. Su, A.I. *et al.* Large-scale analysis of the human and mouse transcriptomes. *Proc. Natl. Acad. Sci. USA* **99**, 4465–4470 (2002).
25. Ramracheya, R.D. *et al.* Function and expression of melatonin receptors on human pancreatic islets. *J. Pineal Res.* **44**, 273–279 (2008).
26. Stumpf, I., Muhlbaier, E. & Peschke, E. Involvement of the cGMP pathway in mediating the insulin-inhibitory effect of melatonin in pancreatic beta-cells. *J. Pineal Res.* **45**, 318–327 (2008).
27. Boden, G., Ruiz, J., Urbain, J.L. & Chen, X. Evidence for a circadian rhythm of insulin secretion. *Am. J. Physiol.* **271**, E246–E252 (1996).
28. Spiegel, K., Leproult, R. & Van, C.E. Impact of sleep debt on metabolic and endocrine function. *Lancet* **354**, 1435–1439 (1999).
29. Turek, F.W. *et al.* Obesity and metabolic syndrome in circadian Clock mutant mice. *Science* **308**, 1043–1045 (2005).
30. Peschke, E. *et al.* Melatonin and type 2 diabetes - a possible link? *J. Pineal Res.* **42**, 350–358 (2007).

¹Oxford Centre for Diabetes, Endocrinology and Metabolism, University of Oxford, Oxford OX3 7LJ, UK. ²Wellcome Trust Centre for Human Genetics, University of Oxford, Oxford OX3 7BN, UK. ³Medical Research Council Epidemiology Unit, Addenbrooke's Hospital, Cambridge CB2 0QQ, UK. ⁴Program in Medical and Population Genetics, Broad Institute of Harvard and MIT, Cambridge, Massachusetts 02142, USA. ⁵Department of Medicine, Harvard Medical School, Boston, Massachusetts, USA. ⁶Center for Human Genetic Research and Diabetes Unit, Department of Medicine, Massachusetts General Hospital, Boston, Massachusetts 02114, USA. ⁷Center for Human Genetic Research, Department of Molecular Biology, Massachusetts General Hospital, Boston, Massachusetts 02114, USA. ⁸Wellcome Trust Sanger Institute, Wellcome Trust Genome Campus, Hinxton, Cambridge CB10 1SA, UK. ⁹Twin Research and Genetic Epidemiology Department, King's College London, St. Thomas' Hospital Campus, Lambeth Palace Rd, London SE1 7EH, UK. ¹⁰deCODE genetics, 101 Reykjavik, Iceland. ¹¹Department of Biostatistics, Boston University School of Public Health, Boston, Massachusetts 02118, USA. ¹²Center for Statistical Genetics, Department of Biostatistics, University of Michigan School of Public Health, Ann Arbor, Michigan 48109, USA. ¹³Department of Epidemiology, Erasmus MC Rotterdam, Postbus 2040, 3000 CA Rotterdam, The Netherlands. ¹⁴Genome Technology Branch, National Human Genome Research Institute, Bethesda, Maryland 20892, USA. ¹⁵Istituto di Neurogenetica e Neurofarmacologia (INN), Consiglio Nazionale delle Ricerche, c/o Cittadella Universitaria di Monserrato, Monserrato, Cagliari 09042, Italy. ¹⁶Department of Biological Psychology, VU University Amsterdam, van der Boechorstraat 1, 1081 BT Amsterdam, The Netherlands. ¹⁷Institute of Health Sciences and Biocenter Oulu, P.O. Box 5000, 90014 University of Oulu, Finland. ¹⁸Department of Clinical Sciences, Diabetes and Endocrinology, Lund University, University Hospital Malmö, Malmö, Sweden. ¹⁹Center for Public Health Genomics, University of Virginia, Charlottesville, Virginia 22908, USA. ²⁰Department of Public Health Sciences, University of Virginia, Charlottesville, Virginia 22908, USA. ²¹Department of Medical Genetics, University of Lausanne, Lausanne 1005, Switzerland. ²²Service of Medical Genetics, Centre Hospitalier Universitaire Vaudois (CHUV), Lausanne 1011, Switzerland. ²³Department of Physiology and Biophysics, Keck School of Medicine, University of Southern California, Los Angeles, California 90033, USA. ²⁴University Institute of Social and Preventive Medicine, Centre Hospitalier Universitaire Vaudois (CHUV), Lausanne 1011, Switzerland. ²⁵Department of Medicine, Division of Endocrinology, Keck School of Medicine, University of Southern California, Los Angeles, California 90033, USA. ²⁶Department of Epidemiology and Public Health, Imperial College of London, Norfolk Place, London W2 1PG, UK. ²⁷Diabetes Research Group, Division of Medicine and Therapeutics, Ninewells Hospital and Medical School, Dundee, UK. ²⁸Center for Neurobehavioral Genetics, University of California, 695 Charles E. Young Drive South, Los Angeles, California 90095, USA. ²⁹Institute for Clinical Diabetology, German Diabetes Center, Leibniz Institute at Heinrich-Heine-University, Düsseldorf, Germany. ³⁰Diabetes and Metabolism Disease Area, Novartis Institutes for BioMedical Research, 100 Technology Square, Cambridge, MA 02139, USA. ³¹Helmholtz Zentrum Muenchen, National Research Center for Environmental Health, Institute of Epidemiology, Neuherberg, Germany. ³²Malmiska Municipal Health Center and Hospital, Jakobstad, Finland. ³³Swiss Institute of Bioinformatics, Switzerland. ³⁴EMBL-EBI, European Bioinformatics Institute, Wellcome Trust Genome Campus, Hinxton, UK. ³⁵Department of Medicine, University of Kuopio and Kuopio University Hospital, Kuopio, Finland. ³⁶Medical Genetics/Clinical Pharmacology and Discovery Medicine, Glaxo SmithKline, King of Prussia, Pennsylvania 19406, USA. ³⁷Skaraborg Institute, Skovde, Sweden. ³⁸Department of Clinical Sciences, Community Medicine, Lund University, University Hospital Malmö, Malmö, Sweden. ³⁹Department of Genetics, University of North Carolina, Chapel Hill, North Carolina 27599, USA. ⁴⁰Population Pharmacogenetics Group, Biomedical Research Centre, Ninewells Hospital and Medical School, Dundee, UK. ⁴¹Department of Obstetrics and Gynaecology, Oulu University Hospital, Finland. ⁴²Department of Child and Adolescent Health, National Public Health Institute (KTL), Aapistie 1, P.O. Box 310, FIN-90101 Oulu, Finland. ⁴³Institute of Biometrics and Epidemiology, German Diabetes Center, Leibniz Institute at Heinrich-Heine-University, Düsseldorf, Germany. ⁴⁴Savitaipale Health Center, 54800 Savitaipale, Finland. ⁴⁵Unità Operativa Geriatria, Istituto per la Patologia Endocrina e Metabolica, Rome, Italy. ⁴⁶Department of Internal Medicine, Erasmus MC, Postbus 2040, 3000 CA Rotterdam, The Netherlands. ⁴⁷Department of Psychiatry, University Medical Center Groningen, Hanzeplein 1, 9713 GZ Groningen, The Netherlands. ⁴⁸Department of Medicine, Helsinki University Hospital, University of Helsinki, Finland. ⁴⁹Diabetes Unit, Department of Health Promotion and Chronic Disease Prevention, National Public Health Institute, Helsinki 00300, Finland. ⁵⁰South Ostrobothnia Central Hospital, Senäjoki 60220, Finland. ⁵¹Institute of Medical Informatics, Biometry and Epidemiology, Ludwig Maximilians University, Munich, Germany. ⁵²Gerontology Research Center, National Institute on Aging, Baltimore, Maryland 21224, USA. ⁵³Department of Public Health and Primary Care, Strangeways Research Laboratory, University of Cambridge, Cambridge, UK. ⁵⁴Department of Psychiatry, Leiden University Medical Center, Postbus 9600, 2300 RC Leiden, the Netherlands. ⁵⁵Department of Psychiatry, EMGO Institute, Institute of Neuroscience, VU University Medical Center, A.J. Ernststraat 887, 1081 HL Amsterdam, The Netherlands. ⁵⁶Department of Internal Medicine, Centre Hospitalier Universitaire Vaudois (CHUV), Lausanne 1011, Switzerland. ⁵⁷Division of Endocrinology, Diabetes, and Hypertension, Brigham and Women's Hospital, Harvard Medical School, Boston, Massachusetts, USA. ⁵⁸The National Heart, Lung, and Blood Institute's Framingham Heart Study, Framingham, Massachusetts, USA. ⁵⁹Institute of Molecular Medicine, Biomedicum, 00290 Helsinki, Finland. ⁶⁰Massachusetts Institute of Technology, The Broad Institute, Cambridge, Massachusetts 02141, USA. ⁶¹Faculty of Medicine, University of Iceland, 101 Reykjavik, Iceland. ⁶²Department of Preventive Medicine, Keck School of Medicine, University of Southern California, Los Angeles, California 90089, USA. ⁶³General Medicine Division, Massachusetts General Hospital, Boston, Massachusetts, USA. ⁶⁴These authors contributed equally to this work. Correspondence should be addressed to G.R.A. (goncalo@umich.edu), J.B.M. (jmeigs@partners.org), N.J.W. (nick.wareham@mrc-epid.cam.ac.uk) or M.I.M. (mark.mccarthy@drl.ox.ac.uk).