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Identification of seven loci affecting mean telomere length and their association with disease

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Abstract

Inter-individual variation in mean leukocyte telomere length (LTL) is associated with cancer and several age-associated diseases. Here, in a genome-wide meta-analysis of 37,684 individuals with replication of selected variants in a further 10,739 individuals, we identified seven loci, including five novel loci, associated with mean LTL ($P<5x10^{-8}$). Five of the loci contain genes (*TERC, TERT, NAF1, OBFC1, RTEL1*) that are known to be involved in telomere biology. Lead SNPs at two loci (*TERC* and *TERT*) associate with several cancers and other diseases, including idiopathic pulmonary fibrosis. Moreover, a genetic risk score analysis combining lead variants at all seven loci in 22,233 coronary artery disease cases and 64,762 controls showed an association of the alleles associated with shorter LTL with increased risk of CAD (21% (95% CI: 5–35%) per standard deviation in LTL, p=0.014). Our findings support a causal role of telomere length variation in some age-related diseases.

Telomeres are the protein bound DNA repeat structures at the ends of chromosomes, which have an important role in maintaining genomic stability[1]. Furthermore, they play a critical role in regulating cellular replicative capacity[2]. During somatic cell replication, telomere length (TL) progressively shortens due to the inability of DNA polymerase to fully replicate the 3' end of the DNA strand. Once a critically short TL is reached, the cell is triggered to enter replicative senescence and subsequently cell death[1, 2]. Conversely, in germ cells and

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URLs

R software, www.r-project.org; 1000 Genomes Project, http://www.1000genomes.org/; Genotype-Tissue Expression Project, http://www.genome.gov/gtex/; UCSC Genome Browser http://genome.ucsc.edu/.

AUTHOR CONTRIBUTIONS

V.C. and N.J.S. supervised the overall study. V.C., M.M., T.D.S., P.vd.H. and N.J.S designed the study. M.M.,T.E., D.R.N, R.A.d.B., G.D.N., D.S., N.A., A.J.B.,P.S.B., P.R.B.,K.D., M.D., J.G.E.,K.G., A.L.H., A.K.H., Lennart Karssen, J.K.,N.K.,V.L., I.M.L., E.M.v.L., P.M., R.M., P.K.E.M., S.M., M.I.M., S.E.M, E.M., G.W.M, B.A.O., J.P., A.P., Annette Peters, Anneli Pouta, I.P.,S.R.,V.S.,A.M.V.,N.V.,A.V.,H.E.W.,E.W.,G.W.,M.J.W.,K.X.,X.X.,D.J.v.V., A.L.C., M.D.T., A.S.H., A.I.F.B., P.J.T, N.L.P., M.P., J.D., W.O., Jaakko Kaprio, N.G.M., C.M.v.D, C.G., A.M., D.I.B., M.R.J., W.H.v.G., P.E.S., T.D.S., P.vd.H. and N.J.S. contributed to recruitment, study and data management, genotyping and/or imputation of individual studies. V.C., J.L.B., M.K.M., R.A.d.B., J.P., E.D., L.K., H.P., P.T.J., and I.H., performed telomere length measurements. C.P.N., E.A.,M.M., J.D., J.L.B.,J.J.H.,K.F.,T.E.,I.S.,L.B.,D.R.N.,R.A.d.B.,P.S.,S.H.,G.D.N.,P.F.O.,I.M.L., S.E.M., and P.vd.H., undertook association analysis of individual studies; C.P.N., E.A., and J.R.T. carried out the meta-analysis and the additional reported analyses. H.Z., X.W., D.G. and Y.D. provided data on telomerase activity and genotypes. J.E., M.P.S., S.K and H.S. contributed CAD association data on behalf of CARDIoGRAM. V.C and N.J.S prepared the paper together with C.P.N., E.A., M.M and P.vd.H. and all authors reviewed the paper.

COMPETING FINANCIAL INTERESTS

The authors declare no competing financial interests

other stem cells requiring renewal, TL is maintained by the enzyme telomerase, a ribonucleoprotein which contains the RNA template *TERC* and a reverse transcriptase TERT[3]. Both longer and shorter TL are associated with increased risk of certain cancers[4, 5], and reactivation of telomerase, which by-passes cellular senescence, is a common requirement for oncogenic progression[6]. Therefore, TL is an important determinant of telomere function.

Mean TL shows considerable inter-individual variability and has high heritability with estimates varying between 44–80%[7–9]. Most of these studies have measured mean TL in blood leukocytes. However, there is evidence that within an individual, mean TL of leukocytes (LTL) and other tissues is highly correlated[10, 11]. In cross-sectional population studies mean LTL is longer in women than in men and is inversely associated with age (declining by between 20–40 base-pairs (bp) per year)[9, 12–14]. Furthermore, shorter age-and sex-adjusted mean LTL has been found to be associated with risk of several age-related diseases, including CAD[12–15] and has been advanced as a marker of biological ageing[16]. However, the extent to which the association of shorter LTL with age-related disorders is causal in nature remains unclear. Identifying genetic variants that affect TL and testing their association with disease could clarify any causal role.

So far, common variants at two loci on Chr3q26 (*TERC*)[17–19] and Chr10q24.33 (*OBFC1*)[18], that explain <1% of the variance in TL, have shown a replicated association with mean LTL in genome-wide association (GWA) studies. To identify further genetic determinants of LTL we conducted a large scale GWA meta-analysis of 37,684 individuals from 15 cohorts, followed by replication of selected variants in a further 10,739 individuals from 6 additional cohorts.

Details of the studies included in the GWA meta-analysis and in the replication phase are given in Supplementary Note and key characteristics summarised in Supplementary Tables 1a and 1b, respectively. All subjects were of European descent, the majority of the cohorts were population-based and three of the replication cohorts were additional subjects from studies used in the meta-analysis. The genotyping platforms and the imputation method (to HapMap 2 build 36) used by each GWA cohort are summarised in Supplementary Table 2. Mean LTL was measured in each cohort using a quantitative PCR method and is expressed as a T/S ratio (Online Methods, Supplementary Note).

LTL, adjusted for age, sex, and any study-specific covariates was then analysed for association with genotype using linear regression within each study and results adjusted for genomic inflation control factors (Supplementary Table 2). An inverse-variance weighted meta-analysis for 2,362,330 SNPs (Online Methods) was performed with further correction for the overall genomic inflation control factor ($\lambda = 1.007$). The quantile-quantile plot for the meta-analysis is shown in Supplementary Figure 1.

SNPs in 7 loci showed association with mean LTL at genome-wide significance ($P<5x10^{-8}$, Fig 1, Table 1, Fig 2 and Supplementary Fig 2). The association of the lead SNP on chromosome 2p16.2 (rs11125529) was very close to the threshold for genome-wide significance , while the lead SNP in a further locus on 16q23.3 (rs2967374) fell just short of

this threshold (Table 1). We therefore sought further validation of these two loci. We confirmed the association of rs11125529 but not of rs2967374 (Table 1). The combined P value from the GWA meta-analyses and replication cohorts for rs11125529 was 7.50×10^{-10}. There was no evidence of sex-dependent effects or additional independent signals at any of these loci (Online Methods, Supplementary Tables 3 and 4).

Details of key genes in each locus associated with LTL and their location in relation to the lead SNP are given in Supplementary Table 5. The most significantly associated locus we found was the previously reported *TERC* locus on 3q26 (Figs 1 and 2, Table 1)[17]. In addition to this, four further loci – 5p15.33 (*TERT*), 4q32.2 (*NAF1*, nuclear assembly factor 1), 10q24.33 (*OBFC1*, oligonucleotide/oligosaccharide-binding fold containing 1)[18] and 20q13.3 (*RTEL1*, regulator of telomere elongation helicase 1) - harbour genes that encode proteins with known function in telomere biology[3, 20–23]. NAF1 is a protein which is required for H/ACA box snoRNA assembly, the RNA family to which *TERC* belongs[20]. Therefore, the three most significantly-associated loci (3q26, 5p15.33 and 4q32.2) harbour genes involved in the formation and activity of telomerase. We therefore examined whether the lead SNPs at these loci as well as the other identified loci associate with leukocyte telomerase activity in available data from 208 individuals. We did not find significant association of any of the variants with telomerase activity (Supplementary Table 6). However, the study only had 80% power (α of 0.05) to detect a SNP effect that explained 3.7% of the variance in telomerase activity and therefore smaller effects are likely to have been missed in this exploratory analysis.

We also replicated the previously reported *OBFC1* locus[18]. OBFC1 is a component of the telomere binding CST complex also containing CTC1, and TEN1[21]. In yeast this complex binds to the single stranded G overhang at the telomere and functions to promote telomere replication. RTEL1 is a DNA helicase that has been shown to play important roles in setting telomere length, telomere maintenance and DNA repair in mice[22, 23]. However, it should be noted that the lead SNP lies 94 kb from *RTEL1*. The remaining two loci (19p21 and 2p16.2) do not harbour obvious candidate genes related to telomere biology. The locus on 19p12 contains a cluster of genes encoding zinc finger proteins (ZNFs) while that on 2p16.2 spans both the *ACYP2* gene which encodes a muscle specific acylphosphate and *TSPYL6*, a gene within intron 3 of *ACYP2* that shares homology with nucleosome assembly factors. There is evidence that *ACYP2* is linked to stress induced apoptosis in rat muscle[24].

In order to gain better functional insight into the associated loci we undertook various bioinformatics analyses (Online Methods). Details of the findings are given in the Supplementary Note and in Supplementary Table 7. SNPs in high LD with the lead SNP were found to lie within potential regulatory elements of *TERC*, *NAF1* and *OBFC1*. However, similar SNPs were also present for other genes in some of the loci. These findings emphasise that although strong candidate genes are located in some of the loci, at this stage we cannot overlook the potential involvement of other genes within each region.

Each of the identified loci explains a relatively small proportion of the total variance in LTL (Table 1). In order to put this in context, we calculated the effect of the lead SNP at each locus in terms of equivalent age-related shortening of LTL based on an estimate of age-

related attrition in T/S ratio calculated across all cohorts (Supplementary Fig 3). We saw per-allele effects using this measure equivalent to between 1.9–3.9 years of age-related attrition in T/S ratio (Table 1). The qPCR method used here to measure LTL cannot be used to directly calculate the effect on LTL in base pairs (bp). However, many prior studies that have used Southern blotting to measure LTL have shown that mean LTL attrition rate is about ~30 bp per year[8, 12–14, 25]. This suggests that the per allele effect of the different SNPs on LTL in base pairs ranges from ~ 57 to 117 bp (Table 1).

As both shorter and longer mean LTL have been linked to increased risk of various diseases, we searched genetic association databases for disease associations with the LTL associated SNPs (Supplementary Table 8). The rs10936599 (*TERC*) allele associated with longer LTL associates with increased risk of colorectal cancer[19] and with two autoimmune diseases, multiple sclerosis (longer LTL allele) and celiac disease (shorter LTL allele). The lead SNP for the 5p15.33 (*TERT*) locus is associated with different cancer types (both shorter and longer LTL alleles) and with increased risk of idiopathic pulmonary fibrosis (shorter LTL allele), a disease that has previously been shown to be associated with shorter LTL[26].

One of the most widely reported associations for LTL to date has been that between shorter mean LTL and CAD[12–14, 25]. Because LTL is also affected by other risk factors for CAD such as oxidative stress[27–29], it has been unclear whether the association of shorter LTL with CAD is primary or secondary. To investigate whether the association could be causal, we examined the association of both individual lead SNPs and a genetic risk score (GRS) based on a combination of all seven SNPs, (adjusted for their effect size) with CAD in the CARDIoGRAM GWAS meta-analysis comprising 22,233 CAD cases and 64,762 controls of European descent[30], using the approach recently described by the ICBP Consortium[31]. Although the results for individuals variants were not significant, 6 out of 7 variants showed consistency in direction and the combined GRS analysis showed a significant association ($p = 0.014$) of the allele associated with shorter LTL with increased risk of CAD (Fig 3). Shorter mean LTL equivalent to one SD in LTL was associated with a 21% (95% CI 5% – 35%) higher risk of CAD.

Here, we report five novel and confirm two previously reported loci that associate with mean LTL in humans. A specific motivation for our study is the observation that variation in LTL is associated with several age-related diseases and the desire to establish whether this link is causal. This is particularly challenging to disentangle because other environmental and life-style factors also impact on TL[29, 32–34]. The most persuasive evidence for a causal role comes from *in vitro* and *in vivo* manipulation of telomerase activity which impacts on TL and has been shown to enhance or reverse senescence and ageing-associated phenotypes[35–39]. Here, we show that some of the genetic variants associated with LTL are also associated with risk of specific cancers as well as other diseases some of which have been shown to be previously associated with shorter LTL, suggesting a causal link. An interesting finding was that alleles associated with both shorter and longer telomeres showed associations with specific cancers suggesting that variation in LTL in either direction may contribute to the development of specific cancers.

As an example of a complex disease that has been shown to be associated with shorter LTL we examined CAD. Through an analysis of a large GWA database of CAD[30], we found that while individually the lead SNPs at each of the TL-associated loci were not significantly associated with risk of CAD (probably at least in part reflecting their weak individual effects on LTL and low power), in a combined analysis, alleles associated with shorter LTL were associated with a significantly higher risk of CAD. Because the variants at each of the loci could have other biological effects that could impact on their association with CAD through LTL (and possibly explain why the NAF1 locus may be trending in the opposite direction), some caution is required in the interpretation of this association. Nonetheless, the finding is consistent with that in the prospective WOSCOPS study where, after adjustment for other CAD risk factors, baseline LTL was associated with a 44% higher risk of CAD over the ensuing mean 5.5 years of follow-up in individuals in the tertile with the shortest LTL compared with the longest LTL[13]. Our finding here therefore supports a causal association of shorter LTL with CAD and further mechanistic investigation of this relationship is warranted.

In summary, we provide novel insights into the genetic determination of a structure that is critically involved in genomic stability and cellular function. Our findings suggest that variants in several genes encoding proteins with known function in telomere biology as well as other genes influence LTL. The findings provide a framework for a genetic approach to investigating the causal role of telomere length in ageing-related diseases.

Online Methods

Subjects

A total of 37,684 individuals from 15 cohorts were used in the GWAS meta-analysis, along with a further 10,739 individuals from 6 cohorts for replication of selected variants.. All individuals were of European descent. Full details of the discovery and replication cohorts are given in the Supplementary Note and key characteristics summarised in Supplementary Table 1.

Telomere Length Measurements and QC analysis

Mean LTL was measured using a quantitative PCR-based technique[40, 41] in all samples. This method expresses telomere length as a ratio (T/S) of telomere repeat length (T) to copy number of a single copy gene (S), within each sample. To standardise across plates either a calibrator sample or a standard curve were used for quantification. LTL measurements were made in five separate laboratories. Laboratories used are listed for each cohort in Supplementary Table 1 and specific details for the methods used are given in Supplementary Note. The majority of the samples (67% of the total) were run in a single laboratory with mean inter-run coefficients of variation for LTL measurements in individual cohorts ranging between 2.7% and 3.9%. The remaining samples were run across 4 other laboratories (Supplementary Note). Mean LTL was first assessed for age-related shortening and for an association of longer LTL with female sex in all cohorts and showed expected associations (Supplementary Tables 1a and 1b).Ranges in T/S ratios were found to vary between cohorts measured in different laboratories (Supplementary Table 1), largely due to differences in the

calibrator or standard DNA used. We therefore standardised LTL within each cohort using a Z-transformation approach. The Z-transformation was performed separately for males and females for sex-stratified analysis. Effects of age, adjusted for sex, on LTL were estimated in a multiple regression model on untransformed and Z-transformed TL in each study separately and combined using a random-effects meta-analysis in STATA (version 11.2, Supplementary Fig 3).

Genotyping, GWAS analysis and study level QC

All discovery cohorts had genome-wide genotype information generated on a standard genotyping platform and include imputed genotypes based on HapMapII CEU build 36 as a reference. Detailed information about individual genotyping platforms, imputation methods, and analysis software is provided in Supplementary Table 2.Within each cohort SNP associations with LTL were analyzed by linear regression assuming additive effects with adjustment for age and sex as well as study specific covariates where appropriate, such as adjustments for family and population structure (Supplementary Table 2). All study-specific files underwent extensive quality control procedures before meta-analysis. All files were checked for completeness and plausible descriptive statistics on all variables partly supported by the gwasqc function in R. Allele frequencies were checked for compliance with HapMap. In addition to the study-specific quality control filters, we included SNP results of a study in our meta-analysis only if the SNP imputation quality score was >0.5 and if the minor allele frequency was >1%. Only SNPs which were available in >50% of the total sample size over all studies were analyzed, resulting in a total number of 2,362,330 SNPs in the meta-analysis.

Meta-analyses

Meta-analysis of all individual study associations was conducted using inverse variance weighting in Stata. As a measure for between study heterogeneity I^2 was calculated[42]. For SNPs with $I^2 \leq 40\%$ fixed-effects models were applied and random-effects were applied for SNPs with $I^2 > 40\%$. Fixed-effects results were verified by an independent analyst using METAL[43]. Before meta-analysis, standard errors of each study were genomic control corrected using study specific lambda estimates as provided in Supplementary Table 2. The overall inflation factor lambda of the meta-analyzed results was 1.007. Results were further corrected for this. SNPs showing association with telomere length with P-values below $5x10^{-8}$, which corresponds to a Bonferroni correction of one million independent tests, were considered to be statistically significant[44].

Replication study

Replication was sought for two SNPs reaching borderline significant p-values in the discovery analysis. Further subsets of NTR and ECGUT along with the Leiden 85-plus study had LTL measurements performed. LTL measurements were available for the GRAPHIC, PLIC cohorts and for additional samples of PREVEND. De-novo genotyping was performed either using a commercial genotyping service (GRAPHIC, PREVEND, KBioscience, UK) or by Taqman genotyping as described previously[45]. In these studies, the same model was applied as in the discovery studies. Single study results were meta-analyzed using inverse-variance weighted fixed-effects models in STATA

Sex stratified analysis

Genome-wide associations were additionally conducted separately in women and men in order to investigate whether sex-specific signals existed. Furthermore, all top SNPs from the overall discovery GWAS, were tested for differences between women and men by means of the normally distributed test-statistic $(beta_w\text{-}beta_m)/sqrt(se_w^2+se_m^2)$. The results of this analysis are given in Supplementary Table 3.

Conditional association analysis

Regional association plots were generated using LocusZoom[46] for each of the loci containing significantly associated SNPs. These were assessed to check that further SNPs in high linkage disequilibrium (LD) with the lead SNP also showed some degree of association with TL. This was confirmed; however it was evident that some regions (5p15.33, 10q24.33 and 20q13.3) contained SNPs in low LD with the lead SNP that also showed association to LTL. In order to assess whether independent signals existed at these loci conditional analyses were carried out. Within a subset of studies, a multiple regression model was calculated for each locus including both SNPs. Adjustments were made in the same way as in the single SNP models. Individual study results were meta-analyzed using fixed-effects in R and compared to the meta-analysis results of single SNP models within the same subset of studies. Independency was defined as the percentage-change in the effect estimate between the single and the multiple SNP model being $\leq 25\%$. The data is given in Supplementary Table 4.

Calculations of explained variances

Explained variances were calculated based on the effect estimates (beta) and allele frequencies (EAF) of each single SNP by $2*EAF*(1\text{-}EAF)*(beta^2/var)$ as suggested before[47]. The phenotypic variance (var) is equal to 1 as the analysis was performed using Z-transformed telomere length.

Genetic risk scores

In order to assess the impact of these variants on risk of CAD we performed a multiple SNP risk score analysis as previously described[31]. This method is equivalent to a fixed-effects inverse-variance weighted meta-analysis of the ratio between the two traits. Lookups were performed in CARDIoGRAM[30] [β_1] to obtain the effect sizes for the seven SNPs along with the standard errors for CAD risk. These were then converted to a ratio[β_3] along with its standard error using the estimates from the telomere meta-analysis[β_2]. We removed the BHF-FHS and NBS data from this analysis because they were included in the CARDIoGRAM analysis and to avoid the possibility of reverse causation given the nature of the BHF-FHS sample. The single SNP results were then meta-analysed using fixed-effects with inverse-variance weighting. The pooled estimate can be interpreted as the effect of a standard deviation increase in telomere length on the risk of CAD.

Leukocyte telomerase activity assays

Details of the cohort are given in Supplementary Note. Peripheral blood mononuclear cells (PBMCs) were freshly isolated from whole blood by Ficoll-Pague Premium (Sigma-Aldrich,

St. Louis, MO) gradient centrifugation within 1 hour after blood draw. Isolated PBMCs were stored in a cryopreservation media composed of RPMI-1640, 10% dimethyl sulfoxide and 10% fetal bovine serum at liquid nitrogen tank until further processing. Telomerase activity was assayed by the Telo TAGGG Telomerase PCR ELISA kit (Roche Applied Science, Indianapolis, IN) (TRAP assay) as per the manufacturers' protocol using $2x10^{-5}$ cells/assay. An extract from 2000 cells were used for TRAP reactions. Sample telomerase activity was expressed as ratio of telomerase activity value divided by control HK293 telomerase activity value from 1000 cells. Intra-assay CV was5.9% and inter-assay CV is 4.8%. Telomerase activity was log transformed to obtain better approximations of the normal distribution prior to analysis. Association analyses with genotype were performed using regression and an additive model with adjustment for age, sex and ethnicity. The interaction between SNP and ethnicity was also built in the regression model to test whether the effect of the SNP on telomerase activity is ethnicity dependent. The power of the study to detect a SNP effect on telomerase activity was computed using the Genetic Power Calculator[48].

Bioinformatics analyses

For all analyses we tested lead SNPs and SNPs with an r^2>0.7 to the lead SNP identified through the 1000 Genomes study at each. Functional predictions of any identified coding variants were carried out using PolyPhen2[49] and SIFT[50]. In order to assess whether any variants influenced gene expression we searched two available genome-wide gene expression databases, the monocyte genome-wide gene expression data from the Gutenburg Heart Study[51] and the Genotype-Tissue Expression Project (GTEx) data base, which includes liver, brain and lymphoblastoid cell types. To identify regulatory variants we searched ENCODE data in the UCSC Genome Browser database[52]. to examine whether any SNPs were located within promoter, enhancer or insulator regions (Chromatin State Segmentation), methylation sites (predicted CpG islands and methylation status of the CpG site using data from the Methyl 450K Bead array data and Bisufite sequencing), conserved elements, conserved transcription factor binding sites and regions of known transcription factor binding as shown by transcription factor ChIP-seq.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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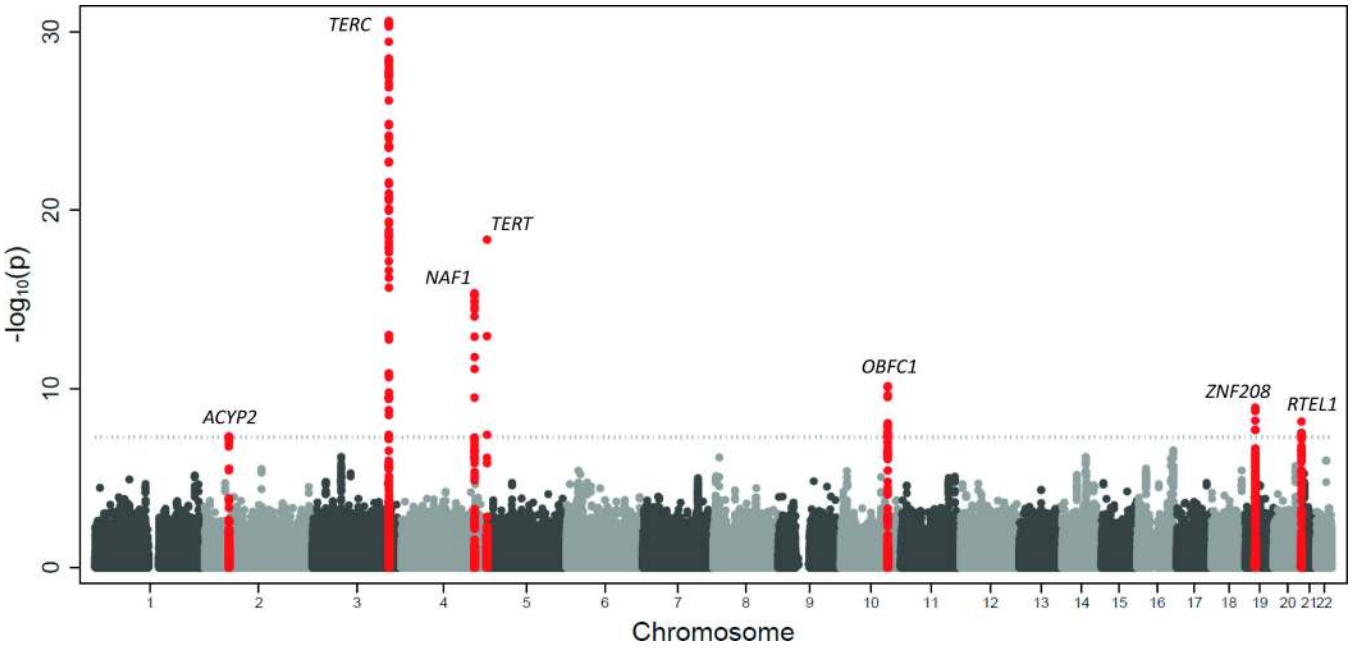

Figure 1. Signal intensity plot of genotype association with telomere length

Data is displayed as –log10P values against chromosomal location for the 2,362,330SNPs that were tested. The dotted line represents a genome-wide level of significance at $P=5x10^{-8}$. The 7 loci that showed an association at this level are plotted in red.

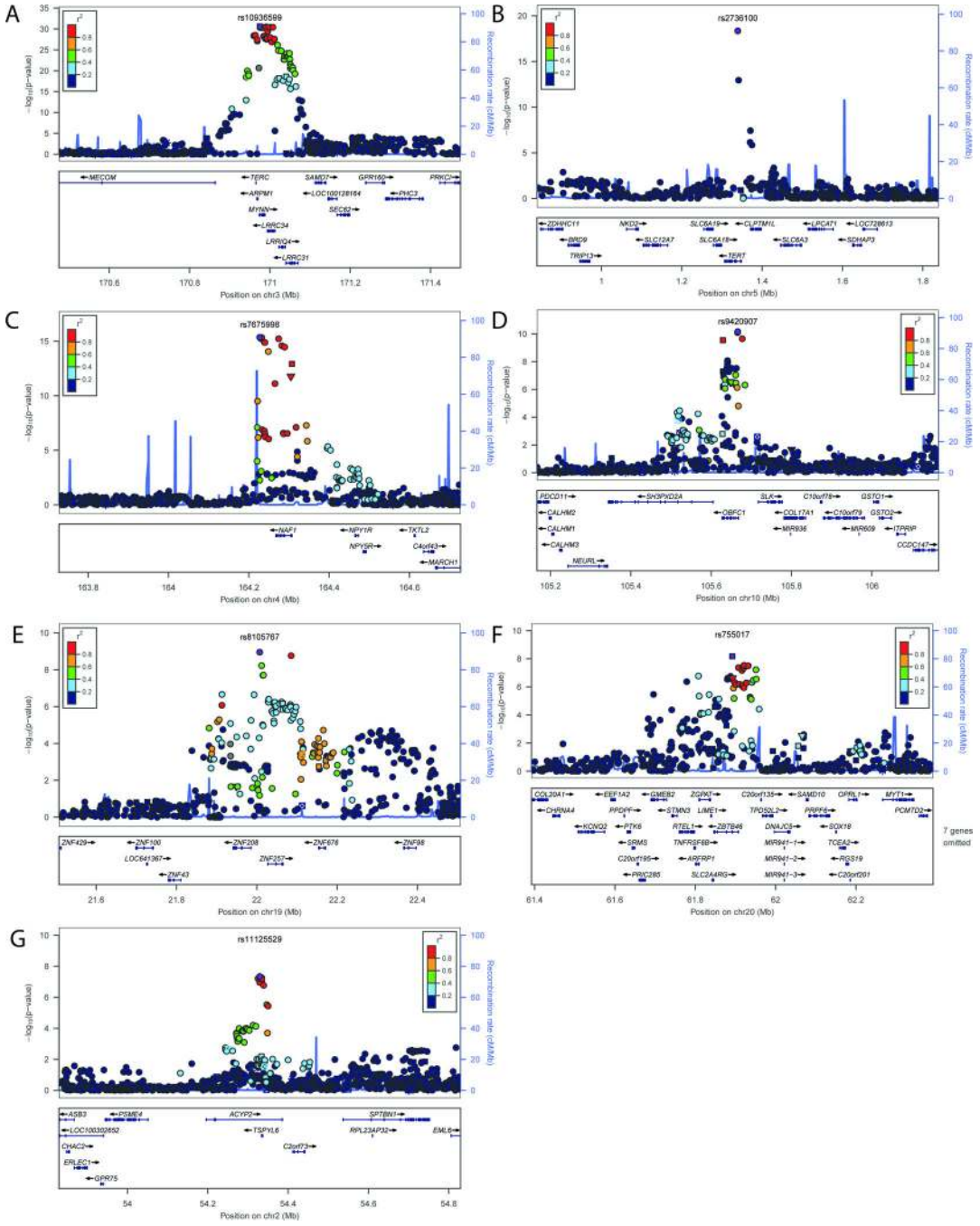

Figure 2. Regional associations plots for the associated loci

For each SNP –log10P is plotted against base pair position for each of the loci (A-G). Regional plots are shown in order of strongest association - Chr3q26 (A), Chr5p15.33 (B), Chr4q32.2 (C), Chr10q24.33 (D), Chr19p12 (E) Chr20q13.3 (F), Chr2p16.2 (G). Within each locus the lead SNP is represented in purple and the LD relationship of other SNPs to this is indicated by the colour as shown in the right hand panel of each plot. Blue peaks represent recombination rates (HapMap 2) and the RefSeq genes within each region are given in the lower panel.

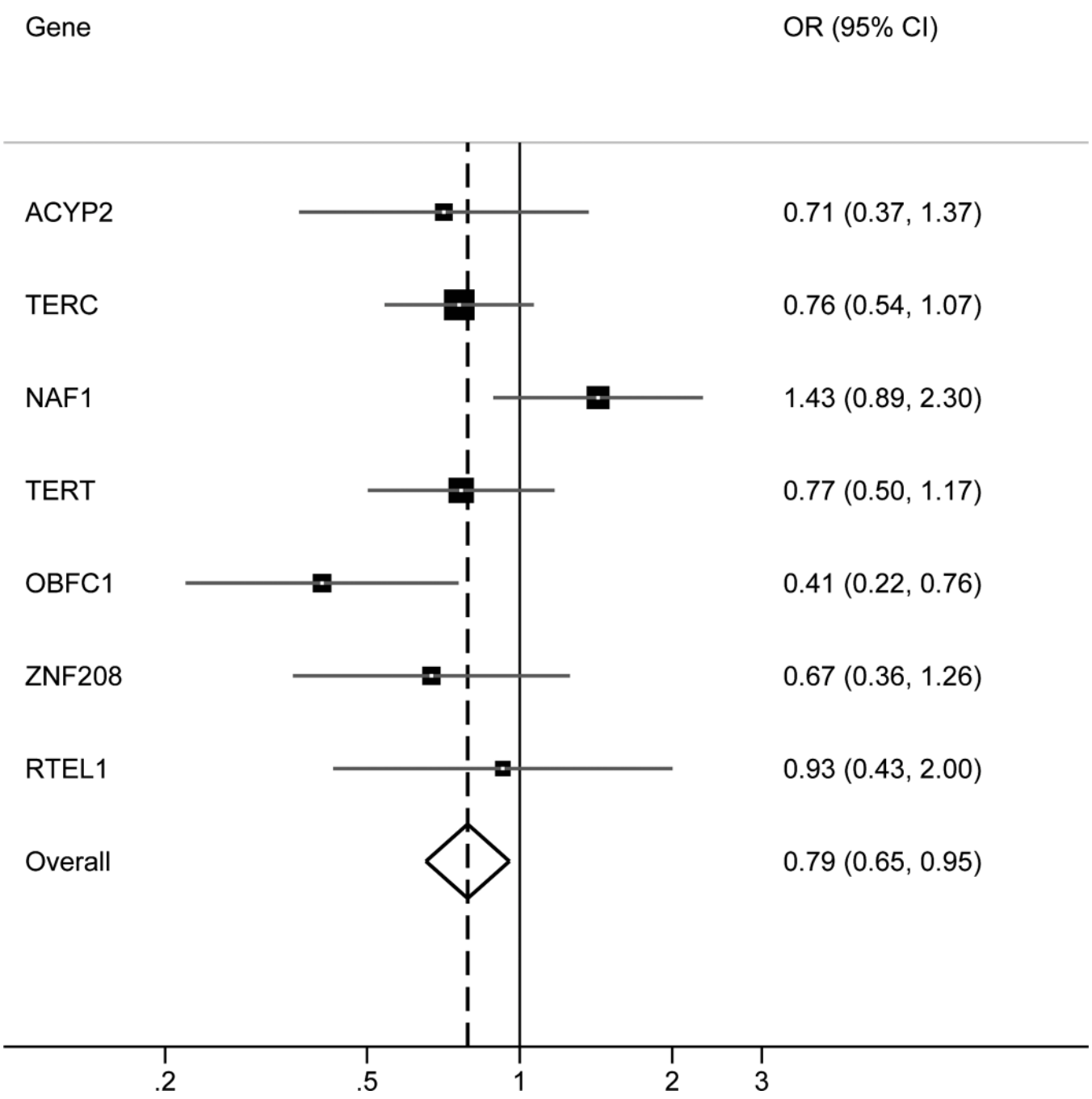

Figure 3. TL variants and risk of CAD

Forest plot showing the effect of telomere length on CAD risk obtained for each SNP using a risk score analysis[31] for each SNP. Effect sizes are plotted with 95% CI intervals. The overall estimate is from a fixed-effects meta-analysis over all SNPs, where the odds ratio relates to the change in CAD risk for a standard deviation change in telomere length.

Table 1

Results of telomere length genome-wide association meta-analysis and replication analysis

N refers to the number of individuals meta-analysed for each SNP and for rs11125529 and rs296734, the additional samples used in replication). The sample size for rs2736100 is smaller than for other loci as this SNP is only present on certain genotyping platforms and due to weak LD structure within the region cannot be imputed reliably. The Effect Allele refers to the allele that is associated with shorter telomere length explaining why all the betas are negative. EAF refers to effect allele frequency.

SNP	Chr	Position	Gene	N	Effect Allele	Other Allele	EAF	Beta	SE	p-value	Explained Variance	Effect on LTL expressed as amount of	
												Equivalent age-related attrition*	Base pairs†
GWA meta-analysis													
rs10936599	3	170,974,795	TERC	37669	T	C	0.252	–0.097	0.008	2.54E-31	0.36%	3.91	117.3
rs2736100	5	1,339,516	TERT	25842	A	C	0.514	–0.078	0.009	4.38E-19	0.31%	3.14	94.2
rs7675998	4	164,227,270	NAF1	34694	A	G	0.217	–0.074	0.009	4.35E-16	0.19%	2.99	89.7
rs9420907	10	105,666,455	OBFC1	37653	A	C	0.865	–0.069	0.010	6.90E-11	0.11%	2.76	82.8
rs8105767	19	22,007,281	ZNF208	37499	A	G	0.709	–0.048	0.008	1.11E-09	0.09%	1.92	57.6
rs755017	20	61,892,066	RTEL1	37113	A	G	0.869	–0.062	0.011	6.71E-09	0.09%	2.47	74.1
rs11125529	2	54,329,370	ACYP2	37653	C	A	0.858	–0.056	0.010	4.48E-08	0.08%	2.23	66.9
rs2967374	16	80,767,362	MPHOSPH6	37437	G	A	0.790	–0.045	0.009	2.70E-07	-	-	-
Selective Replication													
rs11125529	2	54,329,370	ACYP2	10254	C	A	0.864	–0.053	0.070	4.70E-03	-	-	-
rs2967374	16	80,767,362	MPHOSPH6	9063	G	A	0.790	–0.004	0.031	7.80-01	-	-	-

*Estimates of the per allele effect on average age-related telomere attrition in years (based on data in Supplementary Fig 3).

†Estimates of the per allele effect on LTL in base pairs calculated from the equivalent age-related attrition in T/S ratio as described in the main text.