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## Molecular Characterization of the *NLRC4* Expression in Relation to Interleukin-18 Levels

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**Conflict of Interest Disclosures:**

None.

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## Abstract

**Background**—Interleukin-18 (IL-18) is a pleiotropic cytokine centrally involved in the cytokine cascade with complex immunomodulatory functions in innate and acquired immunity. Circulating IL-18 concentrations are associated with type 2 diabetes, cardiovascular events and diverse inflammatory and autoimmune disorders.

**Methods and Results**—To identify causal variants affecting circulating IL-18 concentrations, we applied various omics and molecular biology approaches. By GWAS, we confirmed association of IL-18 levels with a SNP in the untranslated exon 2 of the inflammasome component *NLRC4* (NLR family, CARD domain containing 4) gene on chromosome 2 (rs385076,

$P=2.4 \times 10^{-45}$ ). Subsequent molecular analyses by gene expression analysis and reporter gene assays indicated an effect of rs385076 on *NLRC4* expression and differential isoform usage by modulating binding of the transcription factor PU.1.

**Conclusions**—Our study provides evidence for the functional causality of SNP rs385076 within the *NLRC4* gene in relation to IL-18 activation.

### Keywords

gene expression; transcription factors; gene regulation; genetic variation; Interleukin 18; Inflammasome; PU.1; NLRC4

## Introduction

Interleukin-18 (IL-18), a member of the interleukin-1 family, is a pleiotropic cytokine centrally involved in the cytokine cascade with complex immune-modulatory functions in innate and acquired immunity<sup>1,2</sup>. Circulating IL-18 levels are associated with diverse inflammatory and autoimmune disorders<sup>3</sup>, type 2 diabetes<sup>4</sup> and cardiovascular events<sup>5,6</sup>. The mechanisms through which IL-18 predisposes to these disorders are unknown. Several studies have linked genetic variations in the IL-18 system to circulating biomarker concentrations, disease susceptibility, and progression. Common sequence variants in the four genes that constitute the IL-18 system including *IL18* (MIM 600953), *IL18R1* (IL-18 receptor 1, MIM 604494), *IL18RAP* (IL-18 receptor accessory protein, MIM 604509), and the gene coding for the soluble decoy receptor *IL18BP* (MIM 604113), have been comprehensively genotyped and related to circulating IL-18 levels and cardiovascular events<sup>7,8</sup>. Genome-wide findings confirm associations at the *IL18-BCO2* gene locus on chromosome 11 with circulating IL-18 levels<sup>9</sup>.

In a recent study Matteini *et al.*<sup>10</sup> identified additional genetic variants within an 8.8 Mb region of chromosome 2 spanning the genes *SRD5A2* (MIM 607306), *MEMO1* (MIM 611786), *DPY30* (MIM 612032), *SPAST* (MIM 604277), *SLC30A6* (MIM 611148), and *NLRC4* (MIM 606831) as being associated with circulating IL-18 levels. The *NLRC4* gene (NLR family CARD domain-containing protein 4) was discussed as the most likely inflammation- and thus IL-18-related gene within this region. NLRC4 is a central component of the inflammasome, a multimeric protein complex initiating immune responses<sup>11</sup>. The NLRC4 inflammasome facilitates caspase-1-dependent inflammatory cytokine processing and pyroptosis<sup>11,12</sup>. In addition to sensing microbial pathogens, the function of the NLRC4 inflammasome is the activation of caspase-1 and subsequent proteolytic maturation of pro-IL-18 and pro-IL1 $\beta$  into their active forms<sup>13,14</sup>. Based on the involvement of NLRC4 in IL-18 maturation, it can be hypothesized that *NLRC4* variants are most likely to influence circulating IL-18 levels via inflammasome action. Furthermore, associations of variants within the *NLRC4* locus with serum IL-18 levels were recently confirmed in an IL-18 GWAS in ACS patients<sup>15</sup>. In particular, the authors identified one SNP, rs385076 which was located in a region of the *NLRC4* locus with predicted regulatory relevance. However, both studies<sup>10,15</sup> do not provide molecular data supporting a possible causal association of genetic variants within *NLRC4* and circulating IL-18 levels.

The aims of the present study were (i) to validate genetic determinants of IL-18 by a GWA study, and (ii) to characterize identified loci on a molecular level by cloning the most promising candidate SNP and investigating transcriptomic and epigenetic (i.e. methylation) mechanisms in relation to IL-18.

## Materials and Methods

### Genome-wide association study (GWAS)

We assembled three cohorts for the discovery GWAS, comprising 9,562 individuals of European ancestry, the Gutenberg Health Study (GHS), the Framingham Heart Study (FHS) and the Cooperative Health Research in the Region of Augsburg (KORA F4) Study. For replication, three additional cohorts were included totaling 3,348 individuals (AtheroGene, Monitoring of Trends and Determinants in Cardiovascular Diseases (MONICA/KORA S1/S2/S3), PRIME study). Study protocols were approved by the local ethics committees, and all participants provided written informed consent. Details on the GWAS discovery and replication cohorts are outlined in the Supplementary Material and Supplemental Table 1.

### Genotyping and Imputation

Single nucleotide polymorphisms (SNPs) were genotyped on the Affymetrix Whole-Genome Human SNP Array 6.0 in GHS and KORA F4 and the Affymetrix Human Mapping 500K Array Set and 50K Human Gene Focused Panel in FHS. SNPs were imputed based on the 1000 Genome Phase 1 dataset (version 3 (build 37)). Details of genotyping platform, quality controls, and imputation for each cohort are specified in Supplemental Table 2.

In AtheroGene, MONICA/KORA S1/S2/S3, and PRIME genotyping of rs385076 and rs11606049 (or the respective proxy SNP rs5744222 in MONICA/KORA S1/S2/S3) polymorphisms was performed using 5' nuclease assay (TaqMan assay, Applied Biosystems, Darmstadt) for replication.

## Laboratory analyses

### Measurement of circulating IL-18 levels

In all studies except MONICA/KORA S1/S2/S3, circulating IL-18 levels were measured using a commercially available ELISA (MBL Co, Ltd. Nagoya). The detection limit was 128 pg/mL. Intra-assay CV was 6.9%; inter-assay CV was 13%. In MONICA/KORA S1/S2/S3 serum levels of IL-18 were measured by bead-based multiple assay as described before<sup>4</sup> using an antibody pair and recombinant IL-18 protein from MBL (MBL Co, Ltd. Nagoya). The intra- and interassay coefficients of variation (CV) were <10.0 and <25.0%, respectively. Measurements were performed from deep-frozen samples (−80°C).

### Cloning of NLRC4 rs385076 luciferase reporter gene constructs

To investigate the influence of the SNP rs385076 (T/C) on binding of the transcription factor PU.1, the 908 bp genomic region 32489378 to 32490286 on the antisense strand of the human chromosome 2 comprising the SNP rs385076 (T/C) and the putative PU.1 binding region within untranslated exon 2 of *NLRC4* was amplified by PCR using genomic

DNA from carriers of either the C allele or the T allele of rs385076 (T/C). The PCR products were cloned into the *KpnI*-digested firefly luciferase reporter vector pGL4.10[luc2] (Promega GmbH, Mannheim, Germany). SNP alleles were confirmed by sequencing.

### Cloning of PU.1 overexpression plasmid

For PU.1 overexpression, the PU.1 coding sequence was amplified by PCR using macrophage genomic DNA (Supplemental Table 3) and cloned into *EcoRV*- and *SalI*-digested pVITRO2-MCS (InvivoGen, Toulouse, France). The insert was confirmed by sequencing.

### Transfection of cells and measurement of luciferase activity

HEK293A cells were transfected with 0.5 µg/mL pGL4.10[luc2] containing either the rs385076 C or T allele and 0 µg/mL, 0.125 µg/mL, 0.25 µg/mL or 0.5 µg/mL pVITRO2-PU.1 using 2 µL/mL Lipofectamine2000 (Life Technologies). After 24 h, Bright-Glo Reagent (Promega) was added and cells were immediately frozen at -80 °C for 30 min. Cells were then thawed to room temperature, shaken at 14,000 rpm and luciferase activity was detected via luminescence reader.

### Assessment of NLRC4 isoforms expression

Out of four *NLRC4* isoforms, only isoforms 2 and 4 (ENST00000402280 and ENST00000404025) contain the 5'UTR exon 2. Therefore, the association between expression of *NLRC4* isoforms 2 and 4 and isoforms 1 and 3 (ENST00000360906 and ENST00000342905) with rs385076 genotype was determined. Expression of total *NLRC4* transcript expression, *NLRC4* isoforms 2 and 4, *NLRC4* isoforms 1 and 3 and *GAPDH* as reference gene was measured in monocytes from 1,444 GHS subjects via real-time qPCR using a 7900 TaqMan system (Applied Biosystems). Briefly, RNA was purified using TRIzol (Life Technologies, Darmstadt, Germany) and reverse transcribed using High-Capacity cDNA Reverse Transcription Kit (Life Technologies, Darmstadt, Germany) according to manufacturers' protocols. Real-time PCR was performed in a 10µl reaction volume using 5 µL ABsolute qPCR SYBR Green Mix (Life Technologies, Darmstadt, Germany), 0.2 µl ROX Reference Dye (Jena Bioscience, Oxford, England), 0.25 ng cDNA and 150 – 500 nM primers (Supplemental Table 3). After 15 min activation at 95°C, 40 PCR cycles were run with 15 sec denaturation at 95 °C, 30 sec annealing at 60/62°C and 30 sec extension at 72°C. Primer specificity was verified by melting curve analysis. *NLRC4* mRNA expression was normalized to *GAPDH* as an endogenous control.

### Measurement of DNA methylation

For assessment of DNA methylation sites (CpG sites) in relation to IL-18 levels, genome-wide methylation was performed using the Illumina HumanMethylation450 BeadChip in a subgroup of the KORA F4 cohort (n=1,814) (for details see Supplementary Material).

## Statistical analyses

### Statistical analysis of genotyping data

IL-18 levels showed a skewed distribution and were natural log-transformed for analyses. For genetic association analysis, age- and sex-adjusted linear regression models were applied in all discovery and replication cohorts separately, using an additive genetic model. In GHS, genetic relatedness was considered by identifying and removing outliers based on multidimensional scaling of genetic data prior to GWAS. In FHS, linear mixed effect models were performed to account for relatedness among family members using the function *lmekin* from the R *kinship* package. KORA is a population representative subsample of the population in the study region. Cryptic relatedness in the study sample has been investigated based on genome-wide genotypic data. The degree of relatedness between samples is negligible. Therefore, no further adjustments have been made in this analysis. For meta-analysis, individual estimates of allelic effects from GHS, FHS and KORA F4 were combined after excluding genotyped and imputed SNPs not meeting the quality control filters. An inverse-variance weighted fixed-effects approach was applied as implemented in *METAL*<sup>16</sup>. The genome-wide significance level for the GWAS was set to  $P < 5 \times 10^{-8}$ .

Additive effects of lead SNPs from different loci were tested in all discovery cohorts. SNPs were combined by adding the T allele dosages of rs385076 and rs11606049 for each individual resulting in a number of protective alleles between 0 and 4. The estimated percentage of explained variance for log-transformed IL<sub>e</sub>-18 by SNPs was calculated by subtracting the explained variance of sex and age on log<sub>e</sub>-transformed IL-18 from the multivariable model. For replication in *AtheroGene*, *MONICA/KORA S1/S2/S3* and *PRIME* associations were calculated by applying the inverse-variance based fixed-effects meta-analysis for the selected SNPs.

### Conditional analysis within genome-wide significant loci

To determine if the signals at each locus were independently associated with IL-18 levels, a conditional analysis was carried out in the GHS dataset using the variant with the lowest p-value (with a region of  $\pm 500$ kb) as a lead SNP using *SNPTEST* v2.5 ([www.mathgen.stats.ox.ac.uk/genetics\\_software/snpctest/snpctest.html](http://www.mathgen.stats.ox.ac.uk/genetics_software/snpctest/snpctest.html)), built-in functions.

### Expression quantitative trait loci (eQTL) analysis

Associations between selected SNPs and gene expression of transcripts in *cis* ( $\pm 500$ kb) were assessed for all samples with available gene expression data in GHS ( $n=1,133$ )<sup>17</sup>, and KORA F4 ( $n=699$ )<sup>18</sup>. In both studies, gene expression analysis was performed using the Illumina Human HT-12 v3 BeadChip. Technical variables were used for adjustment as previously described<sup>18</sup>. In both studies, a linear model was used with log<sub>2</sub>-transformed gene expression as dependent variable. For SNP-gene expression analyses data were adjusted for age and sex. PheGenI ([www.ncbi.nlm.nih.gov/gap/phegeni](http://www.ncbi.nlm.nih.gov/gap/phegeni)) and the Geuvadis Data Browser ([www.ebi.ac.uk/Tools/geuvadis-das/](http://www.ebi.ac.uk/Tools/geuvadis-das/)) were used to compare significant eQTLs from our study to publicly available data from large scale studies.

Expression values of *NLRC4* and its isoforms measured by qPCR were normalized for *GAPDH* Ct values prior to association analysis and are represented as deltaCt values ( $\text{deltaCt}_{\text{transcript}} = \text{Ct}_{\text{transcript}} - \text{Ct}_{\text{GAPDH}}$ ). A linear mixed model with the plate as random variable, transcript levels as dependent variable and age and sex as covariates was used to calculate effects of rs385076 allele dosage on *NLRC4* isoform expression. Reported effect sizes refer to the beta from the linear regression, which represents the change of deltaCt per rs385076 T allele.

### Estimating the proportion of variance in IL-18 levels

The proportion of explained variance of log-transformed IL-18 levels attributable to genetic variants was calculated by subtracting the coefficient of variation estimated from a linear model with adjustments for sex and age from the multivariate model, which additionally included the allele dosage as independent variable.

### Association with cardiovascular mortality

Hazard ratios for rs385076 and rs11606049 related to cardiovascular mortality were estimated using Cox proportional hazards regression in the AtheroGene study. Analyses were adjusted for age and sex and an additive genetic model was used.

## Results

### GWA study of circulating IL-18 levels

Characteristics of all discovery and replication cohorts participating in the GWA study are presented in Supplemental Table 1. Figure 1 depicts the Manhattan Plot of our initial GWAS approach demonstrating two regions of genome-wide significance for circulating IL-18 levels. Regional plots of these two regions including functional annotation are presented in Figure 2. Summary GWAS results are available in the Supplemental Table 4. The strongest evidence of association was located within the *NLRC4* gene on chromosome 2 (lead SNP: rs385076,  $P_{\text{meta}} = 2.4 \times 10^{-45}$ ). On chromosome 11, the strongest signal was detected within the *IL18* gene (lead SNP: rs11606049,  $P_{\text{meta}} = 4.6 \times 10^{-35}$ ). Carriers of the respective T allele of both SNPs had lower IL-18 levels. Successful replication of these two SNPs (or the respective proxy SNP rs5744222 in MONICA/KORA S1/S2/S3) was carried out in three independent cohorts (AtheroGene (n=1,165), PRIME (n=440), MONICA/KORA S1/S2/S3 (n=1,743)). T allele frequencies ranged between 35.4% and 39.7% for rs385076 and between 19.9% and 26% for rs11606049 respectively (Table 1). The associations of rs385076 and rs11606049 explained between 2.05% and 2.55% (rs385076) and 1.51% and 3.32% (rs11606049) of the inter-individual variability of IL-18 levels among studies (Table 2). Combination of the lead SNP allele dosages from both loci led to an explained variance between 3.15% (FHS) and 5.49% (GHS) (Table 2). After conditional analysis on the most significant SNP on chromosome 2 (rs385076) and chromosome 11 (rs11606049), no additional SNPs remained significant at the discovery p-value threshold of  $<5 \times 10^{-8}$  (Supplemental Figure 1 A, B).

Our meta-analysis data confirmed previous results of strong associations of circulating IL-18 levels with loci on chromosome 2 and 11<sup>9,10</sup>. For the *IL18* locus on chromosome 11,

previous reports have already investigated the functional consequences of variants within this locus<sup>7,9,20</sup>. However, to our knowledge, for the locus on chromosome 2, no functional data in relation to circulating IL-18 levels have been presented. Therefore, we performed *in silico* and molecular characterization of the *NLRC4* locus.

### In silico functional analysis of the *NLRC4* locus

Regulatory and epigenetic features of the *NLRC4* locus from the Encyclopedia of DNA Elements (ENCODE)<sup>21</sup> and a data set by Pham *et al.*<sup>22</sup> were explored using UCSC Genome Browser<sup>23</sup> and are displayed in Figure 3. The *NLRC4* gene encompasses 4 distinct isoforms and the SNP rs385076 lies within the 5'UTR of the *NLRC4* cDNA, in the untranslated exon 2 included in isoforms 2 and 4. This region directly falls within a region enriched for the H3K27ac histone acetylation mark (often found near active regulatory elements) in human CD14<sup>+</sup> monocytes and several additional cell lines<sup>22</sup>. Furthermore, the region surrounding the SNP rs385076 lies within a DNase hypersensitivity cluster in multiple cell lines as indicated by ChIP-seq data. DNase hypersensitivity is characteristic for open chromatin regions, which are accessible for DNA binding proteins. ChIP-seq data in monocytes<sup>22</sup> showed that strong binding of the transcription factor PU.1 occurs around rs385076. Together, these *in silico* data point towards regulatory region(s) within the *NLRC4* 5'UTR and suggest that different alleles of rs385076 might lead to different *NLRC4* expression levels.

*NLRC4* expression may be affected in several ways: i) a direct effect on *NLRC4* mRNA expression, ii) effects on differential mRNA isoform usage, iii) an effect on *NLRC4* protein level and iv) by modulated binding of transcription factor PU.1. These possibilities were investigated at the molecular level.

### Association of rs385076 and *NLRC4* gene expression

To determine the association of *NLRC4* mRNA expression and the SNP rs385076, the expression data sets of the GHS (monocytes) and KORA F4 (whole blood) studies were used. In monocytes, our data demonstrated an impact of rs385076 on *NLRC4* expression levels with a decrease of *NLRC4* mRNA in carriers of the T allele (beta=-0.037;  $P=3.95\times 10^{-3}$ ). In contrast, in our whole blood dataset, no association between rs385076 and *NLRC4* expression was observed (beta=-0.085;  $P=0.14$ ). We further compared our results to publicly available eQTL data of lymphoblastoid cell lines from 270 individuals<sup>24</sup> using PheGenI. The lymphoblastoid data were in line with our monocytic data, as decreased *NLRC4* mRNA expression for rs479333 C allele carriers (a proxy SNP of rs385076,  $R^2=0.83$ ) was described (beta= -0.133;  $P=3.4\times 10^{-8}$ ). In RNA-seq data from lymphoblastoid cell lines of 373 European individuals from the 1000 Genomes project<sup>25</sup>, which is publicly available at the Geuvadis Data Browser, rs385076 T allele was strongly associated with *NLRC4* gene expression (beta=-0.373;  $P=9.1\times 10^{-14}$ ). A summary of rs385076 and rs479333 eQTLs is provided in Supplemental Table 5.

### Association of rs385076 and *NLRC4* isoform expression

Expression of the *NLRC4* gene including all isoforms as well as two distinct groups of *NLRC4* mRNA isoforms were determined in monocytes of 1,487 GHS participants by



qPCR. The group *NLRC4*<sub>2,4</sub> (encompassing isoforms 2 and 4) includes the rs385076 containing exon 2, whereas the group *NLRC4*<sub>1,3</sub> (encompassing isoforms 1 and 3) does not include the rs385076-exon 2 as depicted in Figure 3.

Consistent with our monocytic gene expression data, overall *NLRC4* expression was decreased in carriers of the rs385076 T allele (beta=0.134; SE=0.05;  $P=6.9\times 10^{-3}$ ). Interestingly, expression of *NLRC4*<sub>2,4</sub> (beta= 0.305; SE=0.047;  $P=2.0\times 10^{-10}$ ) and *NLRC4*<sub>1,3</sub> (beta= -0.103; SE=0.03;  $P=7.4\times 10^{-4}$ ) isoforms were associated with the T allele in opposite directions. Comparing the proportion of *NLRC4*<sub>2,4</sub>/*NLRC4*<sub>1,3</sub> isoforms on overall *NLRC4* gene expression, we observed a shift towards usage of isoforms 1 and 3 in carriers of the rs385076 T allele as depicted in Figure 4. In relation to increased IL-18 concentrations, *NLRC4*<sub>1,3</sub> was significantly lower (beta=0.027; SE=0.014;  $P=0.049$ ), whereas overall *NLRC4* (beta=0.014; SE=0.008;  $P=0.092$ ) and *NLRC4*<sub>2,4</sub> expression (beta=0.009; SE=0.008;  $P=0.254$ ) showed no significant change (Table 3).

### PU.1 binding and influence on *NLRC4* expression in relation to rs385076 alleles

In order to evaluate whether the rs385076 variant influences binding of the transcription factor PU.1 and subsequently *NLRC4* expression, a luciferase reporter gene assay in the presence of overexpressed PU.1 levels were performed. Overexpression of PU.1 was confirmed on mRNA and protein levels (Supplemental Figure 2). Without PU.1 overexpression, no significant difference in luciferase activity between the rs385076 C and T alleles was observed. However, increasing PU.1 concentrations significantly raised luciferase activity in the presence of the rs385076 C allele but not the T allele (Figure 5).

### DNA methylation in relation to circulating IL-18 levels and *NLRC4* expression

We screened for genome-wide associations between DNA methylation in whole blood and circulating IL-18. As shown in Supplemental Figure 3, six CpG-IL-18 associations at the Bonferroni threshold  $1\times 10^{-7}$  were identified. No genome-wide significant CpG sites were found for the chromosome 2 (*NLRC4*) locus. However, two CpG sites cg07055315 and cg22805603 within the *NLRC4* locus showed moderate associations ( $P=2.25\times 10^{-5}$ ;  $P=8.5\times 10^{-3}$ , respectively). Genome-wide significance was found for the two CpG sites on chromosome 16 (cg07839457 ( $P=2.85\times 10^{-12}$ ); cg16411857 ( $P=8.67\times 10^{-08}$ )), both located within the *NLRC5* gene, another member of the NLRC inflammasome protein family.

### Clinical relevance of the IL-18 GWAS loci

As circulating IL-18 levels have been associated to cardiovascular disease (MIM 611139) in previous studies<sup>5,6,28</sup>, a possible link between the SNPs in *NLRC4* and *IL-18* and cardiovascular outcome was investigated. For this, we tested the association of rs385076 and rs11606049 with cardiovascular death in 2,585 coronary heart disease patients of the AtheroGene cohort (median follow-up 4.9 years, maximum 7.6 years, 159 cardiovascular deaths). The rs385076 T allele, related to lower IL-18 concentration, was associated with a protective effect on cardiovascular mortality with an age- and sex-adjusted hazard ratio of 0.78 (95% confidence interval: 0.62–0.98,  $p=0.03$ ). However, the IL-18 lowering allele of rs11606049 was not significantly associated with cardiovascular mortality.

## Discussion

Our study aimed to confirm and functionally characterize genetic determinants of circulating IL-18 levels by molecular approaches. Our molecular data show that the SNP rs385076 affects *NLRC4* expression and differential *NLRC4* isoform usage by influencing the binding of the transcription factor PU.1. Our data suggest that the IL-18-lowering T allele of rs385076 associates with cardiovascular events in a protective manner, thereby providing a link for clinical relevance.

### Molecular analyses of circulating IL-18 levels

**Genetic determinants of circulating IL-18 levels**—Our GWA meta-analysis and replication study revealed two loci, on chromosomes 2 and 11, that associated with circulating IL-18 levels at genome-wide significance. Previous GWA studies reported significant associations of several SNPs on both of these chromosomes with circulating IL-18 levels<sup>9,10</sup>. The *IL18-BOC2* locus associated with IL-18 levels in two independent GWAS samples with the strongest association found for SNP rs2115763, located in intron 2 of *BCO2*<sup>9</sup>. Our data confirmed the strong association of this *BCO2* SNP and showed additional SNPs with even stronger association in the *IL18* gene region, including our top SNP rs11606049 ( $P=4.6\times 10^{-35}$ ). Moreover, our GWAS and conditional studies confirm and extend findings on further genetic determinants of circulating IL-18 identified by Matteini *et al.*<sup>10</sup> and Johannson *et al.*<sup>15</sup> on chromosome 2 and point towards *NLRC4* as the “determinant” locus within this region. SNP rs385076 showed the strongest association of all SNPs in our data (beta: -0.093, SE: 0.007,  $P=2.4\times 10^{-45}$ ) and is located in the untranslated exon 2 (also designated as 5'UTR) of *NLRC4*, suggesting a functional effect of this SNP. This assumption was further strengthened by our *in silico* investigation of the *NLRC4* 5'untranslated region and our experimental data.

**Effect of SNP rs385076 on *NLRC4* gene expression and function**—*NLRC4* encodes a cytosolic protein with a caspase recruitment domain (CARD) found primarily in monocytes and macrophages. Upon activation, *NLRC4* assembles into a multiprotein complex, the inflammasome, which in turn leads to activation of caspase-1 and subsequent maturation of IL-18<sup>13,14</sup>. Our *in silico* functional analyses of the *NLRC4* 5'UTR/exon 2 region point towards the presence of a binding region of the transcription factor PU.1 within the exact region, where the top GWAS SNP (rs385076) is located.

Our molecular data suggested that rs385076 influences the binding of the transcription factor PU.1 to the *NLRC4* 5'UTR region, with reduced PU.1 binding to the *NLRC4* 5'UTR region, in the presence of the IL-18-lowering T allele. The most obvious effect of this influence would be an impact on *NLRC4* mRNA expression. Indeed, our data demonstrated that carriers of the IL-18-lowering T allele of rs385076 had a decreased *NLRC4* mRNA expression in monocytes. Evidence for eQTLs was corroborated *in silico* in two publicly available studies using lymphoblastoid cell lines<sup>24</sup>. In monocytes, we observed decreased expression of *NLRC4* isoforms containing the 5'UTR exon 2 in carriers of rs385076 T alleles (isoforms 2 and 4) and a switch in isoform usage towards those without exon 2 (isoforms 1 and 3). We detected an association between isoforms without the 5'UTR exon 2

and decreased circulating IL-18, but it still needs to be investigated in more detail, whether an enhanced expression of these isoforms leads to reduced activation of IL-18. Compared to monocytes, our analyses in whole blood showed no significant association between rs385076 and *NLRC4* gene expression. Since the inflammasome is mainly active in the innate immune system and is thus more prominent in monocytes, monocyte-specific gene expression might be narrowed by other cell types present in whole blood.

In addition to an influence on PU.1 binding, ENCODE data suggests characteristics for an open chromatin region (hypersensitivity cluster) as well as a binding site for the polymerase 2 (Pol2) around the region of rs385076. Also, phosphorylation of the *NLRC4* protein on a specific serin residue also has been described to play a critical role, possibly by driving conformational changes necessary for inflammasome activation<sup>29</sup>. In our data, SNPs located near this serine residue in the exon 5 also showed a strong association with circulating IL-18 levels (rs408813,  $P=2.5\times 10^{-40}$  and rs455060,  $P=5.04\times 10^{-34}$ ). Epigenetic modifications mirrored by methylation status showed no statistically significant relation of *NLRC4* with IL-18 levels in our data. However, methylation analysis identified an additional inflammasome-linked gene, *NLRC5*, known to play a role in the regulation of IL-18 levels<sup>30,31</sup>. Thus, further experimental work is required to assess the relation between regulatory elements, inflammasome orchestration and IL-18 levels. Our results of the molecular analyses indicate a decreased *NLRC4* gene expression and a switched isoform usage for the rs385076 T allele, putatively modulated by differential PU.1 binding. Since the *NLRC4* inflammasome plays a role in IL-18 activation, our observations are consistent with the finding that rs385076 T alleles lead to lower circulating IL-18 concentrations.

**Genetic variation and cardiovascular mortality**—Since it had previously been shown that circulating IL-18 levels are a marker of cardiovascular mortality in coronary heart disease (CHD)<sup>5,32,33</sup>, we evaluated the association the SNPs rs385076 (*NLRC4*) and rs11606049 (*IL18*) with incident fatal cardiovascular events in 2,585 CHD patients in the *AtheroGene* study. The IL-18-lowering allele of rs385076 was associated with a lower risk of cardiovascular mortality (OR=0.78, 95% CI: 0.62–0.98,  $P=0.03$ ). This observation of an association of the genotype with IL-18 concentrations and potentially clinically relevant outcomes could support a causal relationship in disease evolution. Although variations of the *IL18* gene had previously been shown to influence circulating IL-18 levels and clinical outcome in patients with coronary artery disease<sup>7</sup>, our study did not show an association of our lead *IL-18* SNP rs11606049 with cardiovascular mortality. Since the inflammasome is a central component to inflammatory activity and immune response, our findings may be applicable beyond the cardiovascular system to a broad range of inflammatory and autoimmune diseases<sup>3</sup> and diabetes mellitus<sup>4</sup>. The detailed work-up of the pathophysiological pathways involved in the genetic and posttranscriptional *NLRC4* regulation will show whether causal relations with disease can be identified. Such work may reveal risk indicators and, more importantly, potential therapeutic targets.

### Strengths and Limitations

The present study applies a combination of genetic, molecular and methylation approaches to gain insights into the regulation of circulating IL-18 levels in large, well-characterized

studies. Nevertheless, it is important to address some limitations. The present data are restricted to individuals of European descent and associations may be different in other ethnicities. The question, whether NLRC4 protein levels associate with *NLRC4* gene expression in relation to the SNP rs385076, still remains to be answered. We were not able to show a strong relation of SNP rs385076 with NLRC4 protein levels in peripheral blood mononuclear cells (PBMCs) in 200 individuals from the community-based Gutenberg Health Study (data not shown). This null finding could be due to the low number of samples investigated in rather healthy individuals. Furthermore, the NLRC4 protein was measured in PBMCs, whereas an effect of rs385076 on *NLRC4* gene expression was observed in monocytes. Further in-depth experimental studies as well as sequencing approaches are needed to better understand the implications of these newly identified genetic variants in relation to the exact regulation of inflammatory as well as autoimmune pathways. Lastly, DNA methylation data were only available from whole blood. Here, we did not see a significant association of CpG sites with *NLRC4*. In order to assess whether *NLRC4* expression in relation to IL-18 might be influenced by methylation in a cell-type specific manner, additional methylation analyses, e.g. in monocytes need to be performed.

In summary, using multiple molecular and genetic approaches we confirmed and extended previous knowledge in relation to circulating IL-18 levels within *NLRC4*. Genetic variants in *NLRC4* affect binding of the transcription factor PU.1, suggesting thereby a mediation of the influence on circulating IL-18 levels. The clinical importance of our results is underlined by an association between rs385076 T allele and a lower risk of cardiovascular mortality. The exact mechanisms in relation to cardiovascular disease and other inflammatory and autoimmune diseases needs to be established and should stimulate further epidemiological and experimental studies.

## Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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#### MONICA/KORA

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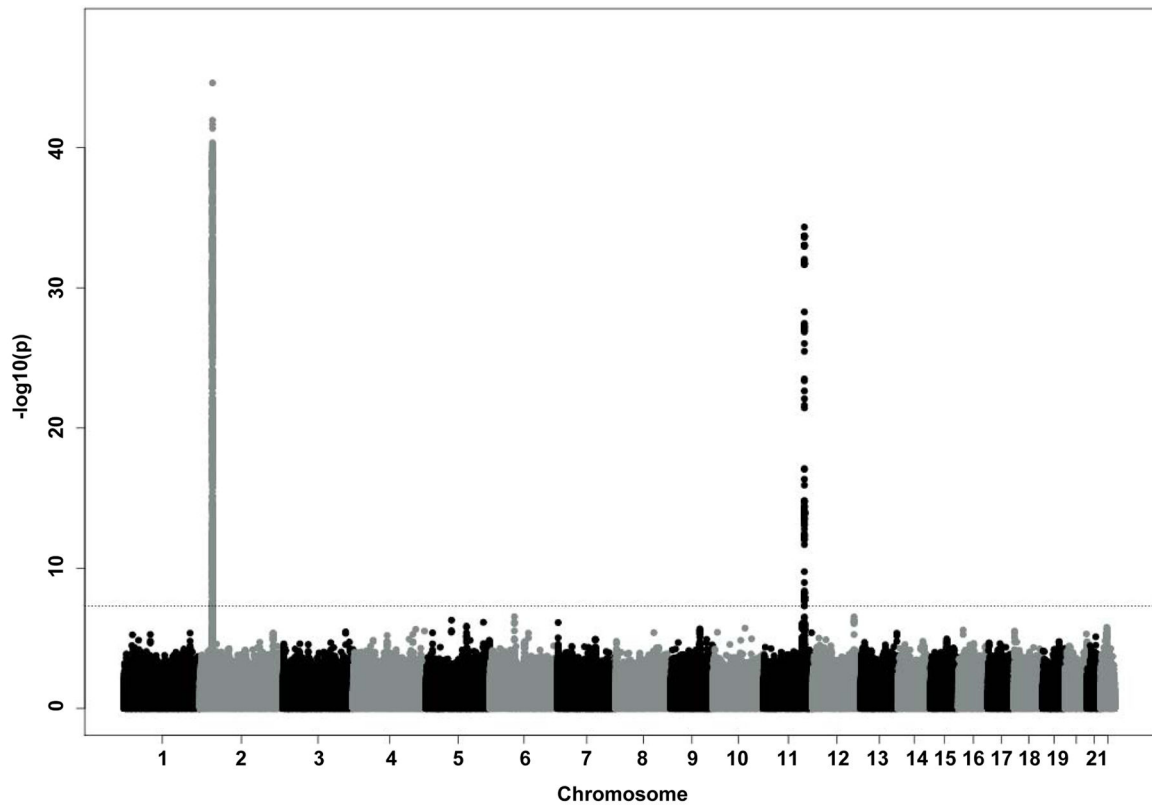
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**Figure 1.** Results from the GWAS meta-analysis of IL-18 concentrations in GHS I, GHS II, FHS and KORA F4. The Manhattan plot shows the associations between allele dosages of 1000-Genomes imputed variants and  $\log_e$ -transformed IL-18 concentrations for all autosomes. The horizontal line indicates the genome-wide significance level ( $P < 5 \times 10^{-8}$ ).



Figure 2 A

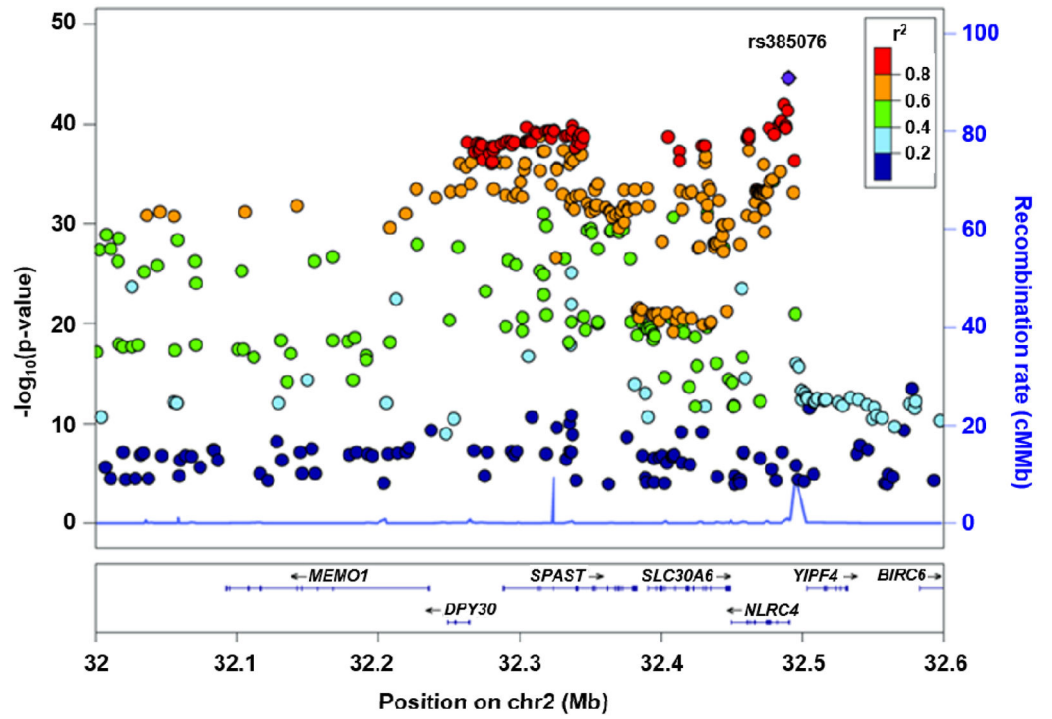


Figure 2 B

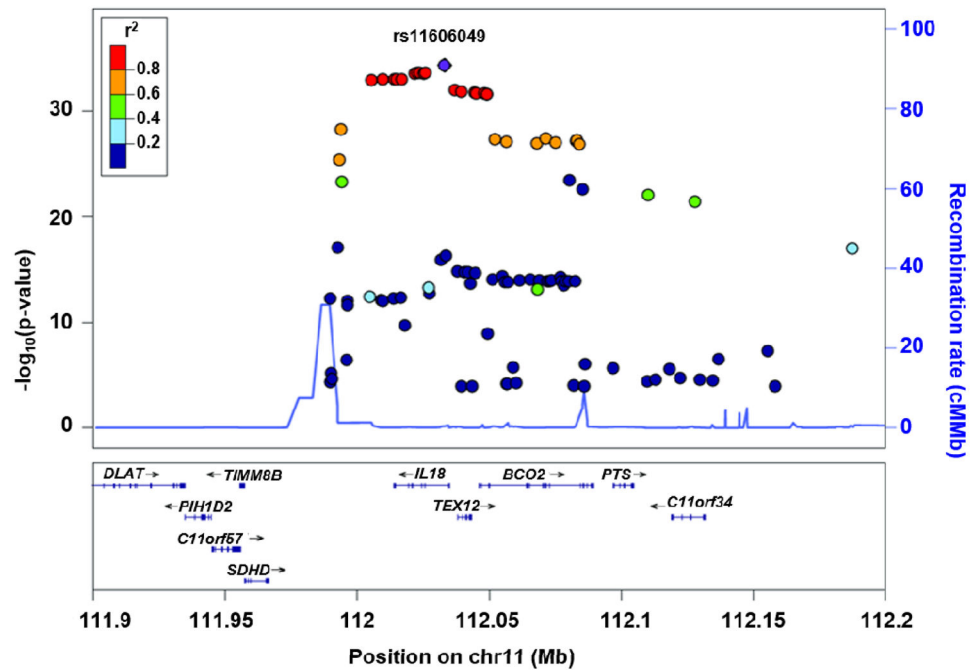
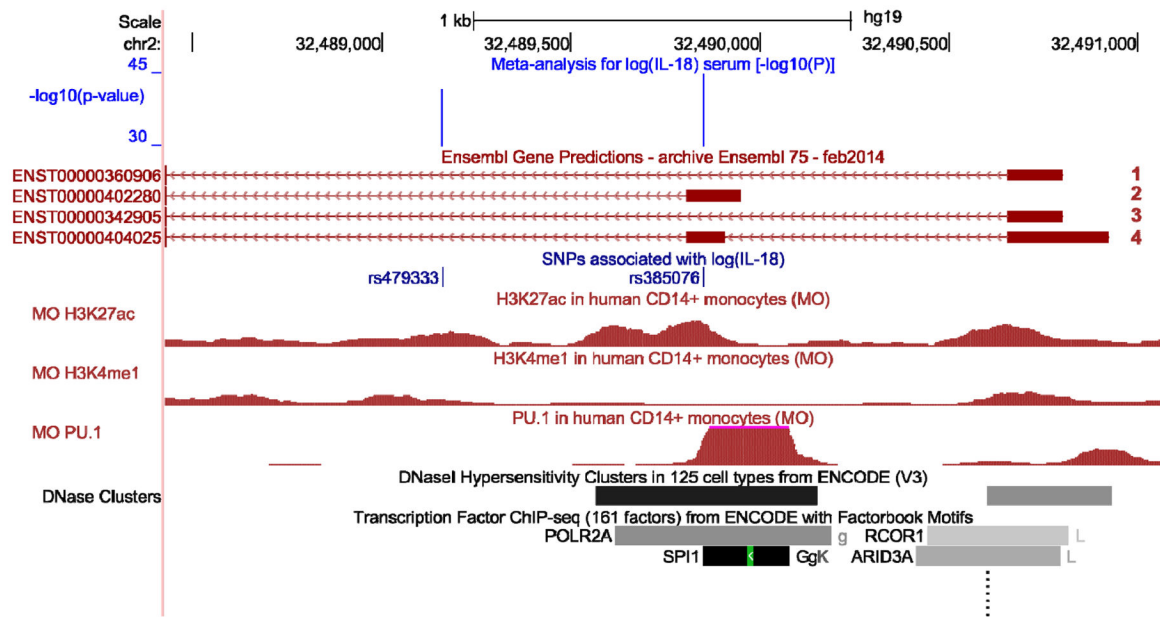


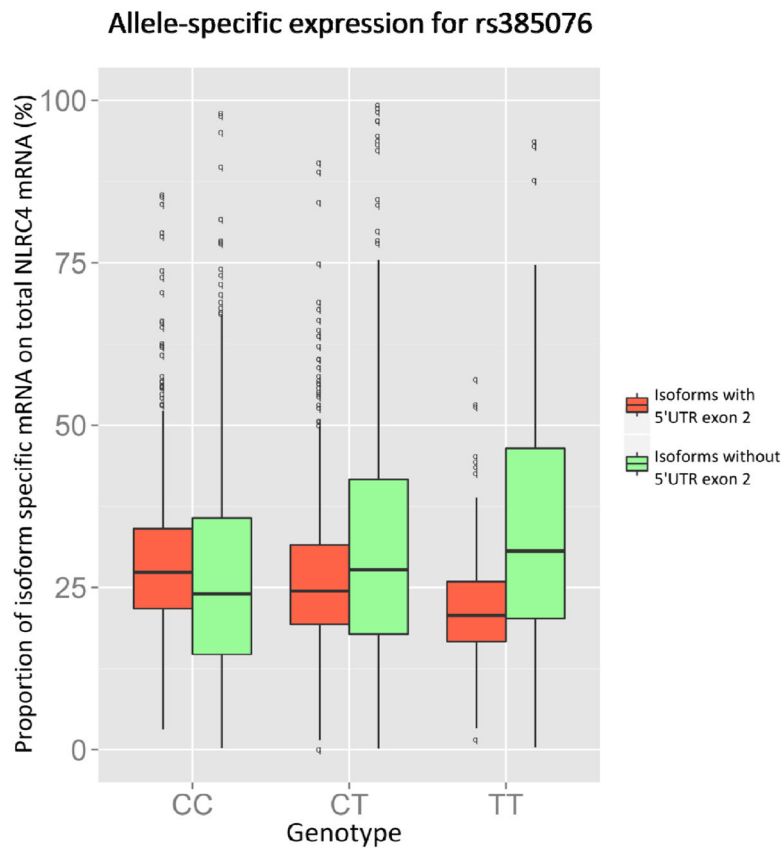
Figure 2.

Regional plot for the *NLRC4* locus (A) and the *IL18* locus (B). P-values of SNPs from  $\log_e$  IL-18 meta-analysis were plotted as  $-\log_{10}$  values against their physical position on chromosome 2 (*NLRC4*) and chromosome 11 (*IL18*), respectively (NCBI build 37). (A) The lead SNP rs385076 on chromosome 2 is represented by a blue diamond and lies within the 5' region of *NLRC4*. (B) The lead SNP rs11606049 on chromosome 11 is represented by a blue diamond and lies within an intronic region of the *IL18* gene. The color code for the pairwise linkage disequilibrium structure is based on 1,000-Genomes 2012 EUR.

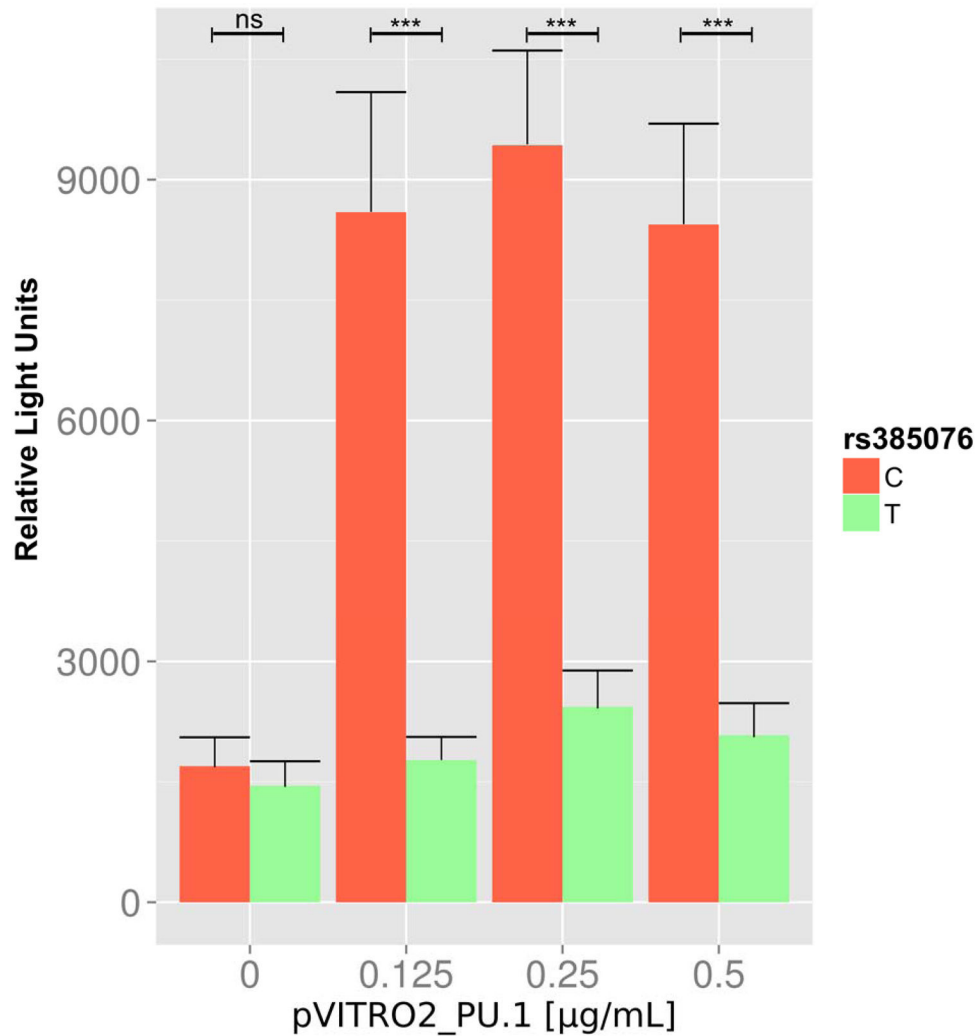


**Figure 3.**

*In silico* functional analyses for rs385076 within the *NLRC4* gene region. Co-localization of IL-18 associated variants and regulatory and epigenetic features were investigated in the UCSC Genome Browser (genome-euro.ucsc.edu) using genome release hg19. Only SNPs with P-values  $<5 \times 10^{-8}$  for the association with circulating IL-18 levels are shown (green track). Tracks showing histone modifications and PU.1 binding sites were uploaded into the UCSC Genome Browser from an external study<sup>22</sup> (red tracks). The PU.1 track represents binding sites of the transcription factor PU.1 in monocytes from a CHIP-seq experiment. The H3K27ac track shows histone modification by acetylation from CHIP-seq experiments in monocytes, which can be considered as a mark for active enhancers<sup>26</sup>. The H3K4me1 mark shows regions undergoing histone methylation, which are likely to reflect cell-type specific regulation of a gene<sup>27</sup>. Enhancer regions are highlighted by DNaseI hypersensitivity clusters from the ENCODE project<sup>21</sup>. In the bottom track, CHIP-seq results for transcription factors (TF) from the ENCODE project are shown, indicating TF binding regions. rs385076 falls into the 5'UTR exon of *NLRC4* and a binding region of PU.1. DNase hypersensitivity clusters around rs385076 suggest a good DNA accessibility in monocytes and histone modification data highlights the region as an enhancer.



**Figure 4.** Allele-specific *NLRC4* isoform expression in relation to the rs385076 genotype. Box plots show the distribution of different isoform usage, which is defined as proportion of isoform expression on overall *NLRC4* gene expression, for each allele of rs385076. All transcripts were quantified by qPCR and normalized for Ct values of the housekeeping gene GAPDH. Isoforms including 5'UTR exon (isoforms 2 and 4) are marked red, others (isoforms 1 and 3) are marked green. We can observe a switch in isoform usage with a higher number of T alleles leading to a higher proportion of transcripts, which do not include 5'UTR exon.



**Figure 5.**

PU.1 overexpression increases *NLRC4* gene expression in relation to the rs385076 C allele. HEK293A cells were transfected with pGL4.10[luc2] plasmid, containing either rs385076 C (shown in red) or T allele (shown in green) and the putative PU.1 binding site, as well as the pVITRO2-PU.1 plasmid. Expression of yellow fluorescent protein after transfection of an empty pEYFP-N1 plasmid was used to control for transfection efficiency. PU.1 overexpression significantly increased luciferase activity of the rs385076 C allele but not the T allele in the plasmids. Without PU.1 overexpression, there was no significant difference between C and T alleles. Cells with 0.125 µg/mL (4.24-fold,  $P=3\times 10^{-4}$ ), 0.25 µg/mL (3.34-fold,  $P=3\times 10^{-4}$ ) and 0.5 µg/mL (3.5-fold,  $P=5\times 10^{-4}$ ) of the pVITRO2-PU.1 plasmid showed significant increases of luciferase activity for the C allele compared to the T allele. ns = not significant, \*\*\*  $P < 0.001$ ;  $n=4$ .

Table 1

Effects of lead SNPs on circulating IL-18 levels in discovery and replication

SNP (coding/non coding allele)	Chr	Gene	Meta-analysis					AtheroGene					PRIME					MONICA/KORA S1/S2/S3				
			Beta	SE	P	AF <sup>†</sup>	Beta	SE	P	Beta	SE	P	AF <sup>†</sup>	Beta	SE	P	AF <sup>†</sup>	Beta	SE	P	AF <sup>†</sup>	
rs385076 (T/C)	2	<i>NLRP4</i>	-0.093	0.007	2.4×10 <sup>-45</sup>	35.6	-0.107	0.017	9.0×10 <sup>-10</sup>	39.7	-0.098	0.032	0.002	35.4	-0.107	0.026	4.0×10 <sup>-5</sup>	36.5				
rs11606049 (T/C)	11	<i>IL18</i>	-0.089	0.007	4.6×10 <sup>-35</sup>	24.5	-0.060	0.020	0.0027	26.0	-0.109	0.029	0.004	19.9	-	-	-	-				
rs5744222 (A/C)			* <sup>‡</sup>	-0.085	0.007	9.2×10 <sup>-32</sup>	75.1	-	-	-	-	-	-	-	-	-0.110	0.030	3.0×10 <sup>-4</sup>				

Beta refers to the effect estimate and SE to the standard error from the linear regression model after adjustment for sex and age. For each SNP, the chromosome (Chr) and nearest gene (Gene) is shown. Discovery meta-analysis in GHS I and II, FHS and KORA F4. AtheroGene, PRIME and MONICA/KORA S1/S2/S3 were used as independent replication cohorts.

\* proxy SNP for rs11606049 with R<sup>2</sup> > 0.9 according to SNAP<sup>19</sup>. † Allele frequency (AF) of the coding allele in %.

**Table 2**

Variance of circulating IL-18 levels explained by SNPs.

Variant (Allele)	Gene	Explained variance (R <sup>2</sup> )			
		GHS I	GHS II	KORA F4	FHS
Sample size		2,743	1,073	1,802	2,940
rs385076 (T)	<i>NLRG4</i>	2.05%	2.22%	2.55%	2.19%
rs11606049 (T)	<i>IL18</i>	1.51%	3.32%	1.89%	1.03%
rs385076 (T) + rs11606049 (T)	<i>NLRG4 + IL18</i>	3.68%	5.49%	4.50%	3.15%

SNPs were combined by adding the allele dosages of rs385076 T and rs11606049 T for each individual resulting in a number of protective alleles between 0 and 4. The R<sup>2</sup> is the estimated percentage of explained variance for log<sub>e</sub>-transformed IL-18 by SNPs. It is calculated by subtracting the explained variance of sex and age on log<sub>e</sub>-transformed IL-18 from the multivariate model.

**Table 3**

Allele-specific *NLRC4* isoform expression in relation to the rs385076 genotype.

Isoforms	Description	Association between mRNA (deltaCt) and rs385076 T alleles				Association between mRNA (deltaCt) and log(IL-18)				
		delta Ct	Beta	SE	P	N	Beta	SE	P	N
2, 4	Including exon 2	5.1±1.4	0.305	0.047	2.0×10 <sup>-10</sup>	1,175	0.009	0.008	0.254	1,459
1, 3	Excluding exon 2	5.2±0.8	-0.103	0.030	7.4×10 <sup>-4</sup>	1,171	0.027	0.014	0.049	1,438
1, 2, 3, 4	Total <i>NLRC4</i> mRNA	3.2±1.3	0.134	0.050	6.9×10 <sup>-3</sup>	1,180	0.014	0.008	0.092	1,467

Expression levels of mRNA are represented as deltaCt values (deltaCt(transcript) = Ct(transcript) – Ct(*GAPDH*)), which are normalized for the housekeeping gene *GAPDH*. Beta estimates were calculated in a linear mixed model and refer to the change in deltaCt for each T allele of rs385076 and the change in log(IL-18), respectively. Therefore, a negative beta implies an increase in gene expression. N refers to the number of individuals with non-missing values used for a test.