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A Genome-Wide Association Study of Circulating Galectin-3

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Abstract
Galectin-3 is a lectin involved in cell-cell interactions and is secreted into the systemic circulation by unknown mechanisms and is increasingly recognised as a potential biomarker with clinical value. Increased circulating levels of galectin-3 have been previously been associated with inflammatory markers, lipids and haematological parameters.

Results
We performed a GWAS analysis of 2,269,099 genotyped or imputed autosomal SNPs (HapMap 2 build 36 CEU panel) in 5,776 subjects of the PREVEND cohort (Table 1, Table S1). All included subjects were of European descent. The quantile-quantile plot for association is shown in Figure 1. There were 2 loci significantly associated with galectin-3 levels (P<5×10^-8) and 11 SNPs showing suggestive evidence (P<5×10^-6 and P>5×10^-8, Figure 2, Table 2). We performed further testing of the lead-SNP of the loci using an additional subset of 3,516 independent subjects derived from the PREVEND cohort (Table 1). Using inverse-variance fixed effect meta-analysis we combined the evidence. None of the suggestive, but both 2 P<5×10^-8 loci of the discovery phase, were confirmed in the independent samples.
One locus harbours the LGALS3 gene and the other locus harbours the ABO gene (Figure 3). The LGALS3 locus accounted for 25.6% of the phenotypic variance. The ABO locus explained 3.8% and together LGALS3 and ABO explained 29.2% of the phenotypic variance. Of note, common genetic variation explained twice the amount of the variation of circulating galectin-3 levels compared to age, age squared (age²), gender, and body mass index combined (11.6%).

Putative causal genetic variants
The lead SNP (rs2274273) of the LGALS3 locus lies in high LD with two non-synonymous variants (rs4644; r² = 1.0 and rs4652; r² = 0.91). As these variants were not present on our platform and not well imputed we wet-lab genotyped these variants and confirmed their association (Table 2). We next considered potential confounding by the specific galectin-3 assay used and noticed the epitopes of the antibodies used are directed against the region harbouring the non-synonymous variant (Figure 4). Therefore, this variant might affect the affinity of the antibody and not represent a true difference in circulating galectin-3 levels. We did not find variants in high LD (r²>0.8) associated with the lead SNP (rs464234) of the ABO locus. Next, we searched for eQTLs in 1,469 samples from peripheral blood for which gene expression levels were obtained using illumine HT12V3 and illumine H8v2 platforms [11]. rs2274273, rs4644, and rs4652 were all associated with LGALS3 gene expression levels (Table 3) and rs2274273 and rs4644 were also the strongest SNP associated with that particular LGALS3 probe. Finally, to gain further insights we queried the catalogue of published genome wide association studies [12] for our loci and observed no previous associations for the LGALS3 locus but many previous genome wide associations findings have been reported for the ABO locus. Previous SNP associations in or near ABO are in high linkage disequilibrium with our lead SNP and include associations with inflammatory markers, lipids and haematological parameters as well as diseases such as cancer and coronary heart disease (Table S2).

Relevance of LGALS3 variant for prognostic value of plasma galectin-3 levels
To study the relevance of the rs2274273 and rs4644 (r² = 1) variant in the LGALS3 locus for the prognostic value of the galectin-3 assay on mortality in the general population we repeated our earlier reported analyses [13] with and without rs2274273 as a covariate in the model. Knowledge of the genotype did not appear to change the prognostic value of plasma galectin-3 levels (Table 4).

Discussion
We report the first genetic association study on galectin-3 levels and identified 2 genome-wide significant loci; one including the galectin-3 encoding gene (LGALS3) and the other gene being ABO.

Galectin-3 is a member of the galectin family that comprises of lectins with affinity for beta-galactosidases containing carbohydrates. The galectin gene family is evolutionarily ancient and can be found in vertebrates, invertebrates, and even in protists suggesting an important role in biology [14]. All galectins have a carbohydrate-recognition domain (CRD) consisting of many conserved sequence elements and each galectin has an individual carbohydrate-binding preference [15]. Galectin-3 is an unique galectin as it contains a non-lectin N-terminal region which is connected to the CRD. Galectin-3 is therefore referred to as a chimera-like galectin [1]. Galectin-3 does not contain a signal sequence and is primarily localised within the cytoplasm. It can be externalized by a mechanism independent of the endoplasmic reticulum (ER)-Golgi complex [16,17]. Galectin-3 has high affinity for lactose and N-acetyllactosamine but can also interact with a wide array of other carbohydrates, membrane and extracellular matrix proteins [18]. Upon ligand binding, galectin-3 (and its ligands) forms cross-links, is involved in strengthening cell-cell interactions, and is associated with stiffening of the extracellular matrix and fibrogenesis. Galectin-3 has been shown to play a role in inflammatory diseases, cancer and heart failure [3,15,19,20]. Little is known about the regulation of galectin-3. The galectin-3 promoter contains several responsive elements, including Sp-1, AP-1 and cAMP responsive elements [21].

We now report the first 2 genome wide associations with circulating galectin-3 levels. The strongest locus is within the LGALS3 gene. The lead SNP (rs2274273) is in full LD with two non-synonymous SNPs (rs4644 and rs4652) which were confirmed by follow-up genotyping. Both rs2274273 and rs4644 affected LGALS3 gene-expression providing a potential explanation for the observed effect. In the current study we also tested whether knowledge of the lead variant in the LGALS3 gene might obscure the association of plasma galectin-3 levels with outcome but it did not alter our previously published associations further supporting a true effect of these variant on galectin-3 [13]. However, some note of caution is warranted. Associations of coding SNPs (e.g. rs4644 and rs4652) that structurally change the properties of its encoded protein can give rise to false positive associations when that protein is also the phenotype under investigation. The non-synonymous SNPs identified in our study also lies within or near the epitopes of the antibodies used for the galectin-3 assay (Figure 4). These antibodies might have different affinities for the amino acid change and therefore this association could also be artifactual. Interference of antibody based assays with epitopes directed against regions harbouring non-synonymous variants are not novel and have previously been reported for the NPPA-NPPB locus when ANP levels were measured [22]. Although gene-expression analyses and associa-
tion with outcome are suggesting a true effect, additional work will be required to define the precise mechanisms of our reported association at the LGALS3 locus.

Our second genome wide locus is the ABO locus. The ABO locus is becoming an increasingly complex and pleiotropic locus. Variants in ABO, and in high LD with our lead SNP (rs644234), have been associated by genome wide association studies with various blood measured traits and diseases. This includes several inflammatory markers, lipids, hematological parameters, cancer, inflammatory diseases, and cardiovascular diseases (Table S2). Interestingly, galectin-3 levels also are associated with many of these conditions. Galectin-3 can indeed bind to polysaccharides of the ABO epitopes and even more strongly to the A- or B-histoblood group epitopes versus the O group [23]. However, this does not explain how the ABO gene variant affects circulating galectin-3 levels.

In summary, we performed a GWAS on plasma galectin-3 levels and identified two genome wide significant loci, one including the LGALS3 gene and the other the ABO gene. The origins of these associations should be further validated by means of functional experiments.

Figure 2. Manhattan plot showing the association of SNPs with circulating galectin-3 levels in a GWAS of 3,776 individuals. The red dotted line marks the threshold for genome-wide significance (P = 5 x 10^{-8}). Two loci reached genome-wide significance. doi:10.1371/journal.pone.0047385.g002

Figure 3. Regional plots at the two significantly associated loci. Horizontal axis indicates chromosomal location and P-values are indicated in the left y-axis. Each plot shows approximately ± 500 kb around each lead SNP and has known gene transcripts annotated at the bottom. The SNPs are colored according to their degree of linkage disequilibrium (r^2) with the lead SNP which is highlighted with a purple diamond and displayed by rs number and significance level achieved in the discovery analysis. doi:10.1371/journal.pone.0047385.g003
Table 1. Galectin-3 levels in the PREVEND cohort, indicated for the total population and for the discovery and replication groups.

| Chr | SNP | A1/A2 | AF     | Effect (se) | P-value | Effect (se) | P-value | Effect (se) | P-value | N   | Location | Nearest Gene |
|-----|-----|-------|--------|------------|---------|------------|---------|------------|---------|------|----------|--------------|
| 2   | rs1775170 | A/G  | 0.27   | 4.79E-02 (0.011) | 3.56E-06 | 3.70E-03 (0.008) | 6.21E-01 | 1.38E-02 (0.006) | 2.43E-02 | 7294 | intronic | SLC9A2       |
| 2   | rs2165179 | A/G  | 0.33   | 4.85E-02 (0.010) | 1.47E-06 | 7.46E-03 (0.015) | 6.28E-01 | 3.17E-02 (0.008) | 1.77E-04 | 7284 | intronic | SCN3A        |
| 6   | rs7586    | T/C  | 0.03   | 1.12E-01 (0.025) | 7.79E-06 | 3.75E-03 (0.017) | 8.21E-01 | 3.69E-02 (0.014) | 7.61E-03 | 7278 | 3'UTR     | COL5A2       |
| 3   | rs1191628 | T/G  | 0.07   | 6.11E-02 (0.013) | 1.37E-06 | 9.69E-03 (0.012) | 4.21E-01 | 3.43E-02 (0.009) | 8.38E-05 | 7289 | intergenic | FLJ25363, PVRL3-AS1 |
| 4   | rs930956  | C/G  | 0.33   | 3.92E-02 (0.009) | 7.84E-06 | 1.34E-02 (0.007) | 5.29E-02 | 2.33E-02 (0.005) | 1.89E-05 | 7277 | intronic | ATP8A1       |
| 5   | rs16902429| G/T  | 0.29   | 3.26E-02 (0.012) | 4.66E-06 | 1.04E-02 (0.007) | 1.22E-01 | 2.09E-02 (0.005) | 1.86E-05 | 7287 | intergenic | COX7C, MIR4280 |
| 6   | rs17658562| T/C  | 0.14   | 5.29E-02 (0.009) | 6.57E-06 | 8.91E-03 (0.010) | 3.65E-01 | 1.67E-02 (0.008) | 2.67E-02 | 7268 | intergenic | MIR548A1, ID4 |
| 8   | rs2409784 | C/A  | 0.75   | 5.29E-02 (0.010) | 1.45E-06 | 1.10E-03 (0.006) | 8.63E-01 | 2.63E-02 (0.006) | 2.29E-02 | 7225 | intronic | BLK          |
| 8   | rs4876386 | C/T  | 0.06   | 6.34E-02 (0.014) | 2.51E-06 | 4.79E-04 (0.007) | 9.48E-01 | 1.42E-02 (0.007) | 2.81E-02 | 7277 | intergenic | MED30, EXI1   |
| 9   | rs644234 | G/T  | 0.35   | 6.05E-02 (0.007) | 4.52E-18 | 7.55E-02 (0.007) | 2.39E-01 | 6.84E-02 (0.005) | 3.65E-01 | 7229 | intergenic | ABO          |
| 11  | rs4351827 | T/C  | 0.25   | 4.98E-02 (0.011) | 2.37E-06 | 4.55E-03 (0.007) | 3.65E-01 | 2.10E-02 (0.006) | 9.14E-04 | 7253 | intergenic | CLMP, MIR4493 |
| 13  | rs9512645 | T/C  | 0.54   | 5.31E-02 (0.011) | 3.43E-06 | 6.06E-03 (0.007) | 4.18E-01 | 1.18E-02 (0.006) | 5.97E-02 | 7281 | intergenic | RASL11A, GTF3A |
| 14  | rs2274273 | A/G  | 0.41   | 1.85E-01 (0.006) | NA      | NA         | -1.85E-01 (0.006) | 2.35E-188 | 3776 | downstream | DLGAP5       |
| 14  | rs46444  | A/C  | 0.41   | 1.85E-01 (0.006) | 2.06E-187 | -1.89E-01 (0.006) | 3.00E-223 | -1.87E-01 (0.004) | 4.97E-465 | 7281 | exonic    | LGALS3       |
| 14  | rs4652   | C/A  | 0.43   | 1.77E-01 (0.006) | 3.48E-173 | -1.79E-01 (0.006) | 1.16E-02 | -1.78E-01 (0.004) | 1.50E-421 | 7292 | exonic    | LGALS3       |
| 15  | rs17223788| C/T  | 0.49   | 5.34E-02 (0.012) | 1.65E-06 | 7.99E-03 (0.006) | 2.14E-01 | 1.93E-02 (0.006) | 5.89E-04 | 7272 | intergenic | LOC283688, ARNT2 |
| 16  | rs8101416 | T/A  | 0.17   | 4.60E-02 (0.010) | 1.94E-06 | 8.56E-05 (0.009) | 9.92E-01 | 2.24E-02 (0.007) | 9.52E-04 | 7257 | intergenic | DUS3L, NRTN |
| 19  | rs12443973| A/C  | 0.20   | 4.80E-02 (0.010) | 2.11E-06 | 5.84E-03 (0.008) | 4.40E-01 | -1.35E-02 (0.006) | 2.55E-02 | 7281 | intergenic | MAF, MIR548H4 |

Significant loci (P<5×10−8, bold) and suggestive loci (P<5×10−6) in the discovery phase that were taken forward for follow-up genotyping. In addition, 2 non-synonymous variants (rs4644 and rs4652) were genotyped. AF: Allele Frequency; (se): standard error.

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Materials and Methods

Study population

We studied subjects included in the PREVEND cohort. The PREVEND cohort has been described in detail elsewhere [13,24,25]. In brief, 4,592 subjects were enrolled in the PREVEND cohort in 1997–1998. Subjects were asked to refrain from eating and drinking prior to their visit (fasting) in the outpatient clinic (between 8:00 a.m. and 1:00 pm) and blood samples were drawn and stored at −80°C. The PREVEND study was approved by the local medical Ethical Committee, and is conducted in accordance with the guidelines of the Declaration of Helsinki. All subjects provided written informed consent.

Galectin-3 Measurements

For 7,968 subjects plasma was available to measure plasma galectin-3 levels [13]. The galectin-3 assay is an enzyme-linked
Table 3. Relationship between identified SNPs with expression of cis-genes in peripheral blood in 1,469 samples.

| Chr | SNP   | Position | Gene   | Probe | P-Value | FDR  |
|-----|-------|----------|--------|-------|---------|------|
| 14  | rs4644 | 54673724 | LGALS3 | 5420377 | 2.42×10⁻⁷ | 0    |
| 14  | rs4652 | 54674789 | LGALS3 | 5420377 | 3.10×10⁻⁶ | 0    |
| 14  | rs2274273 | 54673724 | LGALS3 | 3450685 | 4.45×10⁻⁶ | 0    |

cis-genes: genes within ±1 MB around the lead SNP. FDR: False discovery rate. doi:10.1371/journal.pone.0047385.t003

Gene-expression analyses

We investigated whether expression levels of each of the associated variants had an effect on gene expression levels by mapping cis-expression quantitative trait loci (cis-eQTL) in 1,469 samples from peripheral blood, for which cis-expression level measurements were obtained using Illumina HT12v3 and Illumina H8v2 platforms [26]. Since the cis-eQTLs were imputed using the CEU population of HapMap 2 release 24 as reference, eQTL effects were tested using the imputation dosage values. Effects for SNPs (MAF >5%, HWE >0.001) were considered cis-eQTLs when the distance between the SNP and the midpoint position of the probe was smaller than 1 MB. As multiple testing correction, we controlled the false discovery rate (FDR) at 0.05, by comparing observed p-values to the null distribution obtained from permuting the expression phenotype labels relative to genotype labels 100 times. We also determined the top eQTL SNP for each given probe and tested whether the GWAS SNP had an independent effect on the associated gene expression probe after removing the effect of the top eQTL SNP.

Statistical analysis

Galectin-3 was non-normally distributed and was log transformed before regression analyses. We calculated residuals of galectin-3 levels after adjustment for age, sex, and gender. GWAS analyses were performed on residuals using an additive genetic model in PLINK (v 1.07) [28]. The most significant (P<5×10⁻⁸) SNPs (lead SNP) at each locus was taken forward for further testing. The explained variance of the significant associations was analysed using the directly genotyped variants from the replication stage. Fixed-effect meta-analysis was performed using the variance weighting method of the METAL software package to calculate the overall p-value. The Cox proportional-hazards model was used to calculate the hazard ratio and 95% confidence intervals (CI) of galectin-3. Based on our previous work, sequential models were fitted without and with the SNP of interest [13]. The first model including no covariates (unadjusted) and the second model adjusted for age and gender and the third model adjusted for: age, gender, previous myocardial infarction, previous stroke, hypertension, hypercholesterolemia and diabetes. The assumptions underlying the proportional hazards model were tested and found valid. Analyses were performed using STATA version 11.0 for Windows software (StataCorp LP, College Station, TX, USA).
levels at the Discovery stage.

References

Table S1 SNPs significantly associated with galectin-3

Supporting Information

Table S1 SNPs significantly associated with galectin-3 levels at the Discovery stage.

Table S2 Previous reported traits with genome-wide associations at the ABO locus.

Table 4. Effect of LGALS3 genotype on association of plasma galectin-3 levels on mortality.

Author Contributions

Conceived and designed the experiments: RAdB NV IML PvdH. Performed the experiments: RAdB NV HJW SJLB ACMK LF IML PvdH. Analyzed the data: RAdB NV HJW SJLB ACMK LF IML PvdH. Contributed reagents/materials/analysis tools: RAdB NV HJW SJLB RTG ACMK WH-I LF IML PvdH. Wrote the paper: RAdB NV IML PvdH. Read and commented on the earlier drafts of this manuscript: RAdB NV HJW SJLB RTG ACMK WH-I LF IML PvdH.

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