Genome-Wide Association Study in a Lebanese Cohort Confirms PHACTR1 as a Major Determinant of Coronary Artery Stenosis

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Abstract

The manifestation of coronary artery disease (CAD) follows a well-choreographed series of events that includes damage of arterial endothelial cells and deposition of lipids in the sub-endothelial layers. Genome-wide association studies (GWAS) of multiple populations with distinctive genetic and lifestyle backgrounds are a crucial step in understanding global CAD pathophysiology. In this study, we report a GWAS on the genetic basis of arterial stenosis as measured by cardiac catheterization in a Lebanese population. The locus of the phosphatase and actin regulator 1 gene (PHACTR1) showed association with coronary stenosis in a discovery experiment with genome wide data in 1,949 individuals (rs9349379, OR = 1.37, p = 1.57 × 10⁻⁹). The association was replicated in an additional 2,547 individuals (OR = 1.31, p = 8.85 × 10⁻⁶), leading to genome-wide significant association in a combined analysis (OR = 1.34, p = 8.02 × 10⁻⁶). Results from this GWAS support a central role of PHACTR1 in CAD susceptibility irrespective of lifestyle and ethnic divergences. This association provides a plausible component for understanding molecular mechanisms involved in the formation of stenosis in cardiac vessels and a potential drug target against CAD.

Introduction

Heart disease is a leading cause of illness, disability and death in industrialized countries, particularly in older people [1,2]. The manifestation of CAD follows a well-choreographed series of events that includes the damaging of endothelial cells of the arteries and the gradual deposition of lipids in the sub-endothelial layers [3,4]. CAD is a multifactorial disease, with both acquired and inherited components implicated in its etiology [4]. While most CAD risk factors can be ameliorated through lifestyle changes, such as diet and exercise, inherited causes, i.e. genetic make-up and family history of the disease, are not modifiable [5–7]. A small proportion of CAD cases can be attributed to rare, highly penetrant monogenic effects [8,9], whereas most cases result from the cumulative effect of multiple susceptibility alleles and environmental factors [5,10–13]. Indeed, recent GWAS have identified common variants in several novel candidate genes for cardiovascular disease, such as the CDKN2A/2B/ANRIL gene cluster on 9p21.3, and PHACTR1 on chromosome 6p24.1 [14–16]. However, differences in lifestyle can have major impact on CAD risk and how these may influence the genetic association is largely unknown.
Replication of the GWA results for the most significantly associated polymorphisms in multiple populations with distinctive genetic and lifestyle backgrounds may provide deeper understanding of the pathophysiology of a multifactorial disease like CAD. The current trend in GWA studies relies on genetic analyses of ever increasingly large numbers of individuals, with meta-analysis of cohorts that often are from different phenotypic, genetic and environmental backgrounds as well as with diverse ascertainment schemes [17–19]. A complementary approach lies in the use of smaller but phenotypically well-characterized populations to probe genetic determinants of CAD intermediary phenotypes. Such populations can be especially informative when they have a specific genetic and environment backgrounds. We have carried out investigations of a current trend in GWA studies relies on genetic analyses of ever increasing numbers of participants with the aim of identifying new susceptibility genes for CAD. We performed a comprehensive analysis of published genome-wide association studies (GWAS) for CAD, and identified PHACTR1 as a potential candidate gene for this disease. We carried out a discovery GWAS in 1,949 individuals with CAD and replication phases separately and combined (total). No, mild, and severe correspond to CAD severity categories 1, 2 and 3. Table 1 shows the association of risk factors with different phases. See Methods section for details. Analysis was done in GWA (discovery) and replication phases separately and combined (total). No, mild, and severe correspond to CAD severity categories 1, 2 and 3. 

1. Study Subjects

The study subjects consisted of 4,741 individuals who underwent cardiac catheterization following a single consistent and stringent recruitment protocol between August, 2007 and June, 2009 at several hospitals in Lebanon [21]. Catheterization was prompted for myocardial infarction (MI) (13.1%) as diagnosed by electrocardiogram and high troponin levels, unstable angina (30.3%), or other reasons, such as stable angina, or heart failure, or reversible ischemia by stress testing (56.5%). All patients underwent coronary catheterization by Judkins’ technique. The four main coronary arteries: the left main artery (LMCA), the left anterior descending artery (LAD), the left circumflex artery (LCx), and the right coronary artery (RCA) were visualized from different angles by angiography. Two experienced interventional cardiologists reviewed the coronary angiograms independently. The stenotic lesions in these vessels were assessed and recorded as a percentage of coronary blockage. The extent of the coronary lesion was estimated visually by comparing the reduction in the diameter of the narrowed vessel to a proximal assumed normal arterial segment. Cardiologists performing the coronary angiography collected a 20 mL blood sample from the arterial access site of patients who provided a written consent for the whole study that included blood collection and genetic analysis. Trained healthcare professionals collected further data on the socio-demographic background of all patients. Annotations were coded from medical charts for additional data such as laboratory tests, prescribed medications, and presence of other diseases and conditions. Genomic DNA was extracted using a standard phenol extraction procedure. The Institutional Review Board (IRB) at the Lebanese American University approved the study protocol.

For the primary analysis, patients with a normal angiogram with no visible lesions in any of the four coronary arteries were classified as CAD category 1 and considered as control subjects. Patients with coronary artery stenosis were classified into two categories: CAD category 2 comprised patients with ≤50% stenosis (moderate) in
any coronary artery, and CAD category 3 comprised patients with >50% stenosis (severe) in any of the coronary arteries [22]. For the genome-wide association analysis with CAD degree of stenosis, the comparisons were done among subjects in each of the three CAD categories. For the genome-wide association analysis with site of stenosis for each of the 4 coronary arteries, patients in CAD categories 1 and 2 were compared to CAD category 3 patients.

2. Genotyping

2.1 Whole genome. For the initial discovery phase of the study, DNA samples of the first 2,002 recruited individuals were utilized for whole genome genotyping. A total of 1,210 and 792 individuals were genotyped by Illumina Human610-Quad BeadChip and Illumina Human660W-Quad BeadChip respectively (552,510 overlapping SNPs), as part of the Functional Genomic Diagnostic Tools for Coronary Artery Disease project initiative (FGENTCARD) [21]. Out of the 2,002 genomic DNA samples genotyped, 1,949 non-duplicated samples with quality filtered genotyping data were retained.

2.2 Targeted genotyping. For replication analyses, we have selected (1) all SNPs with p-value $<10^{-5}$ (n = 7) from primary analysis (GWAS phase), (2) SNPs in previously identified candidate genes that showed a p-value $<10^{-5}$ (n = 8) in the GWAS phase and (3) SNPs located in a region of 500 Kb around the eight candidate genes (n = 5). These SNPs were re-genotyped by mass spectrometry (Sequenom, CA) in the initial GWAS sample. In addition, 2,739 independent replication samples from the same ascertainment centers were genotyped by Sequenom mass spectrometry. From the 2,739 genotyped samples, 192 individuals were excluded due to missing clinical and demographic information and the resulting 2,547 samples were analyzed. In addition to the above 20 SNPs, rs12526453 in the PHACTR1 region that has been previously identified to be associated with early-onset MI, and not present on the Illumina chip for the GWAS phase, was selected to be genotyped in the replication cohort.

3. Statistical Analysis

We characterized subjects using ordered (e.g. degree of stenosis) and unordered (e.g. site of stenosis) categorical measures, and continuous variables for analysis. The study was divided into an initial discovery phase based on 1,949 individuals and 2,547 individuals for further genotyping to confirm genome-wide signals. The associations of the CAD stenosis categories with conventional risk factors were examined by Fisher’s exact test for count data, and by ANOVA for continuous valued response variables. We also evaluated the association of these risk factors between GWA and replication phases. For every risk factor, we tested for differences in proportion at each degree of stenosis between the two phases. A one-degree of freedom log-linear analysis on the phase effect was used for the qualitative traits, and two-way ANOVA for the quantitative traits.

All SNPs with over 98% genotyping success rate, minor allele frequency of above 1% and that are in Hardy-Weinberg equilibrium ($p>1\times10^{-7}$) were included in the analysis. All 20 SNPs selected were in HWE (p-value $>1E-4$) and had a MAF more than or equal to 5%. The population substructure (ancestry analysis) was examined by Principal Component Analysis (PCA) using the EIGENSTRAT software [23].

Analyses were based on an additive genetic model. We employed the cumulative logit analysis of the proportional odds model [24] for CAD category data, which was expressed as ordinal categorical data: no, mild and severe stenosis. Three covariates, indicator of genotyping BeadChip, sex, and age at investigation of coronary angiogram, were included in the model as a primary analysis. P values were calculated by likelihood ratio test. A p-value $<5.0\times10^{-8}$ was considered to be genome-wide significant. The replication set included the same categorical phenotype allowing analysis with the same cumulative logit model. The results of the discovery and replication phases were combined by fixed effect meta-analysis using “rmeta” package in R.

Figure 1. Manhattan plot showing results of a GWA analysis in 1949 Lebanese patients for 513,079 SNPs. The Y-axis corresponds to the significance of the association (-log10 p-values). The X-axis represents the physical location of the variant colored by chromosome.

doi:10.1371/journal.pone.0038663.g001
Results

The study population has a mean age of 61.56 (±11.33), 69.2% of the individuals were males with a majority (73%) suffering from 50% stenosis in at least one of the 4 main coronary arteries (CAD category 3) (Table 1). CAD category 3 disease was manifested in 78% of the diabetic subgroup. Similar patterns of disease were observed in those suffering from hypertension, hyperlipidemia or positive family history of CAD. As expected, individuals with severe stenosis showed the highest frequency of the traditional risk factors compared to patients with no or mild stenosis. The results were statistically significant (Table 1).

1. GWAS Results

To map gene loci associated with coronary artery stenosis, SNPs genotyped data in the discovery cohort of 1,949 individuals were tested for association with stenosis category phenotypes. Of the 513,079 successfully genotyped SNPs that overlapped in the two genotyping BeadChips, only one SNP, rs11186734 on chromosome 10, showed genome-wide significance (OR = 0.51, p = 3.94 \times 10^{-10}) for association in the discovery cohort adjusted for indicator of genotyping BeadChip, sex, and age at investigation of coronary angiogram (Figure 1). The genomic control inflation factor (\(\hat{\lambda}\)) [25], which compares observed association statistics against the expected distribution was 1.033 suggesting no systematic over-dispersion of the association statistics (Figure 2). Furthermore, the incorporation of the first 10 components derived from the PGA ancestry analysis as covariates into the association did not affect the results appreciably. Other SNPs showing trend of association were rs13006511 (OR = 0.61, p = 4.88 \times 10^{-7}) on 2q12, rs890049 (OR = 1.43, p = 1.40 \times 10^{-5}) on 2q35 and rs7964864 (OR = 1.72, p = 6.71 \times 10^{-5}). The SNP rs890049 maps to the tensin 1 (TNS1) locus encoding a protein involved in the remodeling of the extracellular matrix. An additional nearby SNP (rs4674220) in TNS1 showed p-value of 5.66 \times 10^{-5} (OR = 1.35). Interestingly, rs9349379 on 6p24, located in the gene encoding the protein phosphatase 1 and actin regulator 1 (PHACTR1), previously associated with early-onset MI[14–16], showed a p-value of 1.57 \times 10^{-5} (OR = 1.37). None of the SNPs in other genomic regions previously associated with cardiovascular disease showed similarly strong association with the degree of coronary stenosis in our analysis [26].
Table 2. Cumulative logit analyses for the most significant SNPs in the GWA phase and the corresponding scores in the replication phase as well as the combined effect from the meta-analysis sorted by the level of significance in the meta-analysis.

<table>
<thead>
<tr>
<th>SNP</th>
<th>Candidate gene</th>
<th>Chr</th>
<th>bp position</th>
<th>Effect allele</th>
<th>Other allele</th>
<th>Frequency of effect allele</th>
<th>Frequency of effect allele</th>
<th>Meta-analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>rs9349379</td>
<td>PHACTR1</td>
<td>6</td>
<td>13011943</td>
<td>G</td>
<td>A</td>
<td>0.342</td>
<td>0.373</td>
<td>1.374</td>
</tr>
<tr>
<td>rs2327620</td>
<td>PHACTR1</td>
<td>6</td>
<td>13015577</td>
<td>A</td>
<td>G</td>
<td>0.52</td>
<td>0.5</td>
<td>0.788</td>
</tr>
<tr>
<td>rs11186734</td>
<td>TNS1</td>
<td>7</td>
<td>20323910</td>
<td>C</td>
<td>T</td>
<td>0.326</td>
<td>0.286</td>
<td>1.332</td>
</tr>
<tr>
<td>rs4674220</td>
<td>TNS1</td>
<td>7</td>
<td>20345232</td>
<td>C</td>
<td>T</td>
<td>0.173</td>
<td>0.149</td>
<td>0.606</td>
</tr>
<tr>
<td>rs1300511</td>
<td>GCC2-LIMS1</td>
<td>2</td>
<td>108405522</td>
<td>C</td>
<td>T</td>
<td>0.111</td>
<td>0.108</td>
<td>1.23</td>
</tr>
<tr>
<td>rs6974002</td>
<td>MACC1-ITGB8</td>
<td>7</td>
<td>20345232</td>
<td>C</td>
<td>T</td>
<td>0.018</td>
<td>0.042</td>
<td>1.25</td>
</tr>
<tr>
<td>rs7919192</td>
<td>Histone cluster</td>
<td>6</td>
<td>20345232</td>
<td>C</td>
<td>T</td>
<td>0.018</td>
<td>0.042</td>
<td>1.25</td>
</tr>
</tbody>
</table>

Alleles follow forward strand of NCBI36 reference genome. OR (odds ratio) was calculated from major homozygote as a baseline. 95%CI is a 95% confidential interval of OR.

doi:10.1371/journal.pone.0038663.t002
2. Replication Results

In order to confirm the association, a selection of 20 SNPs were genotyped for replication with the Sequenom technology in the entire cohort (n = 4,496). Concordance for genotypes between the Illumina GWAS and the Sequenom data was 99% for all SNPs. With the notable exception of SNPs in the PHACTR1 locus, none of the other SNPs showed any improvement of the results in the meta-analysis (Table 2). The SNP rs9349379 (Figure 3) showed strong association in the replication phase (OR = 1.31, p = 8.85 \times 10^{-10}), and its significance was improved in the meta-analysis (OR = 1.34, p = 8.02 \times 10^{-10}). Another variant in PHACTR1, rs12526453, which major allele C was previously reported to be associated with increased risk (OR = 1.15) of early-onset MI [15,16], was not in the exploratory genome-wide BeadChip, but part of our replication effort (OR = 0.82, p = 8.9 \times 10^{-4} for the minor allele G). Interestingly, our at-risk allele G of rs9349379 (freq = 0.39 in the replication cohort) occurred in the background of the common at-risk allele C of rs12526453 (freq = 0.62 in the replication cohort) showing strong Linkage Disequilibrium in our replication cohort at the haplotype level only (D’ = 0.98, r^2 = 0.37). Testing for independence between these 2 signals with a multilocus analysis, we validated that our new variant rs9349379 explained most of the association observed in rs12526453; the size of its effect dropping from OR = 1.22 to OR = 1.05. Most importantly, the SNP rs9349379 still showed strong association with degree of stenosis independent of MI status (OR = 1.34, p = 2.94 \times 10^{-9}). The respective significance of SNPs in the PHACTR1 locus was further elucidated in the context of regional recombination and LD (Figure 3) [27].

The SNPs were also tested for stenosis association with each of the four main coronary arteries. Sorted by arteries, rs9349379 in PHACTR1 most strongly impacted LAD, with an odds ratio of 1.33 (95% CI = 1.22–1.44, p = 6.04 \times 10^{-12}), followed by RCA and LCx (Table 3).

Discussion

Here we report the first genome-wide scan for genetic susceptibility to variable degrees of coronary artery stenosis in a Middle East population. We demonstrate strong association with variants in the PHACTR1 gene that was previously implicated in early-onset MI [14–16]. GWA studies conducted in ethnically distinct and geographically distant populations with varying dietary habits, environmental exposures and differing cultures provide useful comparisons yielding knowledge about the contribution of specific genetic variants to increasingly prevalent diseases worldwide [16,28,29]. The design methodologies followed in these studies often display distinctive inclusion criteria and a variety of parameters have to be taken into account to carry out the necessary comparative analysis and interpretation. Variability in study enrollment, such as family-based, cohort, and case-control comparison strategies, as well as the use of different inclusion and exclusion criteria, with variations applied even between screening and validation stages of individual studies, all impact risk estimates. Most importantly, CAD outcomes are classified by varying standards. While some use coronary angiography to firmly verify the disease status, others consider healthy individuals from the general population as controls [16,28,29]. One of the strengths of our study lies in the phenotypic characterization that is based on stringent case-control definition criteria, whereby the percent of stenosis in all four coronary arteries was determined based on angiographic visualization. This study design excluded all asymptomatic individuals with angiographic CAD from the control.
PHACTR1 Is Associated with Coronary Artery Disease

The meta-analysis of the exploratory and the replication sets showed strong and genome-wide significant evidence for association of SNP rs9349379 in PHACTR1 with arterial stenosis in all arteries. Variants in PHACTR1 were originally associated with early-onset MI in a study published by the MI Genetics consortium [14–16]. The most significant SNP in these studies, rs12526453 [15,16], was not part of our discovery, but showed association in the replication set. However, its effect dropped after taking into account the variant rs9349379 that appears on the same background haplotype (D' = 0.98, r² = 0.37). Our results confirm recent data [14] that suggests that rs9349379 may be a better marker for the association than rs12526453. The role of PHACTR1 in the pathophysiology of cardiovascular disease remains to be elucidated. PHACTR1 is a regulator of protein phosphatase 1 (PP1), an enzyme that regulates endothelial nitric oxide [30], an important modulator of cardiovascular disease [31]. Furthermore, PP1 activity was shown to be elevated in patients with end-stage heart failure [32].

In accordance with two recent publications [14,16], our results confirm that PHACTR1 variants are associated with degree of stenosis independent of MI. Indeed, when specific major vessels were used as a stand-alone outcome variable, the association was highest with the left anterior descending artery (LAD; OR = 1.33, p = 6.04×10⁻⁷) and lowest with the left main artery (LMCA; OR = 1.14, p = 2.75×10⁻⁵) (Table 3). The association was significantly increased proportionate to number of vessels with stenosis, reaching p = 7.27×10⁻¹⁰ when stenosis was present in all 4 vessels (data not shown). Since stenosis in the coronary arteries is a major risk factor for MI, variants in PHACTR1 may at least in part contribute to MI risk through an involvement in the formation of stenosis in the cardiac vessels independently of a role in Ca²⁺ homeostasis of the heart.

The association with rs9349379 remained significant after adjustment for gender, hypertension, dyslipidemia, and diabetes suggesting that these risk factors are not major contributors to the observed association (data not shown). This variant remains significant across different structured populations with diverse dietary and genetic profiles, which demonstrates its strong genetic component in the disease.

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associated SNPs may differ among populations with different lifestyle patterns, or their distribution is such that significant associations cannot be assessed with equal power in the different populations studied.

Although they did not reach the same level of significance, many of the formerly reported variants showed nominally significant p values in the same direction as those reported [26]. The 9p21 locus that was shown to be associated with coronary heart disease in more than one GWAS [16,28,33], in particular variant rs4977574, did not show genome-wide significance for association with CAD (PCA adjusted p = 0.0107) or MI (p = 0.00448) in our study population [28]. Interestingly, a candidate gene approach was used to test association of candidate SNPs with CAD and/or MI in genotypic and allelic association models using logistic regression [26]. Results showed that the variant rs4977574 in CDKN2A/CDKN2B in the 9p21 locus was significantly associated with MI (OR = 1.33, p = 0.006) in the Lebanese population. Association was detected after adjustment for confounding risk factors.

A parallel approach was conducted on a list of 20,225 variants in 80 previously published genes for association in our Lebanese cohort. The study was based on our genome-wide genotype data set, with imputation across the whole genome to CEU HapMap population as a reference. This approach identified a significant association of two new loci with CAD (CDKAL1 and PTPRD), in addition to the CXCL12 locus. Further, we identified ST6GAL1 as having a protective effect against CAD/MI [26].

Our results contribute to ongoing efforts aiming at identifying genes associated with the multifaceted CAD and can provide important perspectives in disease diagnosis as well as new avenues for drug discovery.

Acknowledgments
We thank the patients for agreeing to participate in the study. We thank Nour Moukalled and Bariaa Khalil for their help with subject recruitment and data collection. We thank the Rafic Hariri University Hospital, “Centre Hospitalier du Nord” and Saint Georges Hospital, Lebanon for their collaboration and support.

The FGENTCARD Consortium: Dominique Gaugnié, The Wellcome Trust Centre for Human Genetics, University of Oxford, UK; Mark Lathrop, Jörg Hager, CEAnoGenomics Institute, Centre National de Génopépide, Evry, France; Jeremy K. Nicholson, Imperial College London, UK; Pierre Zalloua, Lebanese American University, School of Medicine, Beirut, Lebanon; Ulla Grove Sideleman, Novo Nordisk, Måløv, Denmark; Frank Bonner, Metabometrix Ltd, London, UK.

Author Contributions
Conceived and designed the experiments: JH DG MF DEP JR DZ IG ML.Performed the experiments: SY AKS. Analyzed the data: DEP JH YK MGS JR GK PAZ. Contributed reagents/materials/analysis tools: DAB MH AKS BD RO NS SK HS EC HEB. Wrote the paper: MGS SY DEP PAZ.

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