Original Investigation

Association Between a Genetic Variant Related to Glutamic Acid Metabolism and Coronary Heart Disease in Individuals With Type 2 Diabetes

Lu Qi, MD, PhD; Qibin Qi, PhD; Sabrina Prudente, PhD; Christine Mendonca, BA; Francesco Andreozzi, MD, PhD; Natalia di Pietro, PhD; Mariella Sturma, MS; Valeria Novelli, PhD; Gaia Chiara Mannino, MS; Gloria Formoso, MD, PhD; Ernest V. Gervino, ScD; Thomas H. Hauser, MD, MMSc, MPH; Jochen D. Muehlchlegel, MD, MMSc; Monika A. Niewczas, MD, PhD; Andrzej S. Krolewski, MD, PhD; Gianni Biolo, MD, PhD; Assunta Pandolfi, PhD; Eric Rimm, ScD; Giorgio Sesti, MD; Vincenzo Trischitta, MD; Frank Hu, MD, PhD; Alessandro Doria, MD, PhD, MPH

IMPORTANCE Diabetes is associated with an elevated risk of coronary heart disease (CHD). Previous studies have suggested that the genetic factors predisposing to excess cardiovascular risk may be different in diabetic and nondiabetic individuals.

OBJECTIVE To identify genetic determinants of CHD that are specific to patients with diabetes.

DESIGN, SETTING, AND PARTICIPANTS We studied 5 independent sets of CHD cases and CHD-negative controls from the Nurses' Health Study (enrolled in 1976 and followed up through 2008), Health Professionals Follow-up Study (enrolled in 1986 and followed up through 2008), Joslin Heart Study (enrolled in 2001-2008), Gargano Heart Study (enrolled in 2001-2008), and Catanzaro Study (enrolled in 2004-2010). Included were a total of 1517 CHD cases and 2671 CHD-negative controls, all with type 2 diabetes. Results in diabetic patients were compared with those in 737 nondiabetic CHD cases and 1637 nondiabetic CHD-negative controls from the Nurses' Health Study and Health Professionals Follow-up Study cohorts. Exposures included 2 543 016 common genetic variants occurring throughout the genome.

MAIN OUTCOMES AND MEASURES Coronary heart disease—defined as fatal or nonfatal myocardial infarction, coronary artery bypass grafting, percutaneous transluminal coronary angioplasty, or angiographic evidence of significant stenosis of the coronary arteries.

RESULTS A variant on chromosome 1q25 (rs10911021) was consistently associated with CHD risk among diabetic participants, with risk allele frequencies of 0.733 in cases vs 0.679 in controls (odds ratio, 1.36 [95% CI, 1.22-1.51]; P = 2 × 10⁻⁸). No association between this variant and CHD was detected among nondiabetic participants, with risk allele frequencies of 0.697 in cases vs 0.696 in controls (odds ratio, 0.99 [95% CI, 0.87-1.13]; P = .89), consistent with a significant gene × diabetes interaction on CHD risk (P = 2 × 10⁻⁴). Compared with protective allele homozygotes, rs10911021 risk allele homozygotes were characterized by a 32% decrease in the expression of the neighboring glutamate-ammonia ligase (GLUL) gene in human endothelial cells (P = .0048). A decreased ratio between plasma levels of γ-glutamyl cycle intermediates pyroglutamic and glutamic acid was also shown in risk allele homozygotes (P = .029).

CONCLUSION AND RELEVANCE A single-nucleotide polymorphism (rs10911021) was identified that was significantly associated with CHD among persons with diabetes but not in those without diabetes and was functionally related to glutamic acid metabolism, suggesting a mechanistic link.

The prevalence of type 2 diabetes has been steadily increasing in the United States and other countries, with the total number of affected people reaching more than 370 million globally. Long-term cardiovascular complications, and especially coronary heart disease (CHD), are the principal causes of morbidity and mortality among diabetic patients. Although mortality caused by CHD has been declining overall during the past few decades in most industrialized countries, the increasing prevalence of diabetes has made the number of CHD deaths attributable to this disease escalate. The role of genetic factors in modulating susceptibility to CHD has been known for many years, and more than 40 chromosomal loci associated with CHD have been identified to date in the general population by genome-wide association studies (GWAS). 

Earlier analyses have shown considerable heterogeneity in genetic effects between diabetic and nondiabetic individuals, probably owing to the distinct mechanisms of atherogenesis in diabetes. This has led us to hypothesize that other, as yet undiscovered loci may exist that affect CHD risk only or mostly in the presence of diabetes. Finding these genes, if they exist, may point to atherogenic pathways that are specifically activated by the diabetic milieu and as such could be the target of new interventions aimed at preventing or treating CHD specifically among diabetic patients.

In this study, we performed a GWAS of CHD targeted to type 2 diabetic participants to identify genetic determinants of CHD that are specific to diabetic patients.

**Methods**

**Study Populations**

Detailed information on the study populations is provided in the eMethods in the Supplement. Briefly, stage 1 included diabetic patients from the Nurses’ Health Study (NHS) and the Health Professionals Follow-up Study (HPFS) (eMethods in the Supplement). CHD cases were defined as those with incident cases after the diagnosis of type 2 diabetes to the end of 2008; controls were participants free of CHD events in the specified period. These studies were approved by the Human Research Committee at the Brigham and Women’s Hospital, Boston, and all participants provided written informed consent.

Stage 2 included diabetic CHD cases and CHD-negative controls from the Joslin Heart Study (eMethods in the Supplement). The study protocol and informed consent procedures were approved by the Joslin Committee on Human Studies and the BIDMC Committee on Clinical Investigations. All participants gave written informed consent.

Stage 3 included diabetic CHD cases and CHD-negative controls from the Gargano Heart Study (cross-sectional design) and the Catanzaro Study (eMethods in the Supplement). The study protocol and informed consent procedures were approved by the local human subject committees. All participants gave written informed consent.

To compare the association between rs10911021 and CHD risk in nondiabetic vs diabetic participants, we analyzed a separate nondiabetic CHD case-control GWAS, which included incident CHD cases and non-CHD controls from the NHS and HPFS cohorts, after excluding individuals affected by diabetes (eMethods in the Supplement). We also obtained data on rs10911021 from the Coronary Artery Disease Genome-wide Replication and Meta-analysis (CARDIoGRAM). To explore whether this variant may contribute to CHD through alterations of insulin sensitivity, we interrogated the Meta-analyses of Glucose and Insulin-Related Traits Consortium (MAGIC) database, a meta-analysis of GWAS data for metabolic traits. We also interrogated the Diabetes Genetics Replication and Meta-analysis (DIAGRAM) database to explore whether this variant might have pleiotropic associations with both type 2 diabetes and CHD.

**Genotyping**

Single-nucleotide polymorphism (SNP) genotyping and imputation for stage 1 have been described in detail elsewhere and in the eMethods in the Supplement. Briefly, samples were genotyped with the Affymetrix Genome-Wide Human 6.0 array. A total of 704,409 and 706,040 SNPs passed quality control in the NHS and HPFS sets, respectively, and were used to impute the genotypes of other SNPs by means of MACH software. In stages 2 and 3, SNPs were genotyped by the Joslin DERC Genetics Core by means of TaqMan assays implemented on an ABI PRISM 7700 HT Sequence Detection System (Applied Biosystems).

**Gene Expression in Endothelial Cell Lines**

To investigate whether the association between rs10911021 and CHD risk could be mediated by gene expression changes, we measured messenger RNA levels of 8 neighboring genes (4 on the centromeric and 4 on the telomeric side) (eFigure 1 in the Supplement) in 124 human umbilical vein endothelial cell lines from nondiabetic mothers. Umbilical cords were obtained from randomly selected healthy mothers who delivered at the Pescara Town Hospital, Italy, and gave written consent to this procedure. Primary human umbilical vein endothelial cell lines were established from the umbilical cords and cultured as described by Gorfljen et al. Cell lines were typed for the rs10911021 SNP with a TaqMan allelic discrimination assay (Applied Biosystems). Gene expression was assayed by means of real-time quantitative polymerase chain reaction-based TaqMan low-density arrays. Eight target genes neighboring rs10911021, along with a housekeeping gene (GUSB; NCBI Entrez Gene NG_016197.1) as endogenous control, were included in the array.

**Amino Acid Measurements**

To obtain further insights into the potential functional influence of rs10911021, we measured plasma glutamine and glutamic acid, as well as the ratio between pyroglutamic acid (the immediate precursor of glutamic acid in the γ-glutamyl cycle) and glutamic acid in 100 diabetic patients from the Joslin Heart Study (50 rs10911021 risk allele C homozygotes and 50 T homozygotes).
Glutamic Acid Metabolism Variant and CHD in Diabetes

Mozygotes). Plasma concentrations of glutamic acid and glutamine were assessed at the University of Trieste, Italy, by gas chromatography-mass spectrometry, using the internal standard technique, as previously described. Known amounts of L-[15N]-glutamic acid and L-[15N]-glutamine (Cambridge Isotope Laboratories) were added as internal standards to a known volume of plasma. Silylated derivatives were measured under electron-impact ionization by selective ion monitoring at a nominal mass-to-charge ratio (m/z) of 432/433 for glutamic acid and 431/432 for glutamine. The pyroglutamic acid derivative was also monitored at a nominal m/z of 300. The pyroglutamic/glutamic acid peak area ratio was determined at nominal m/z of 300 and 432, respectively.

Statistical Analyses
GWAS and Validations
Analyses were carried out in 3 stages. In stage 1, 2 separate GWAS for CHD across 2,543,016 genotyped or imputed SNPs (with imputed SNPs expressed as allele dosage) were performed in the NHS and HPFS sets by means of logistic regression under an additive genetic model with the ProbABEL package. The genomic inflation factor λ was estimated from the median χ² statistic. To control for potential confounding by population stratification, we performed further analyses by including the top principal components of genetic variation chosen for each study in the models (top 3 and 4 eigenvectors for NHS and HPFS, respectively).

Meta-analysis of the 2 GWAS scans was conducted by combining study-specific β-estimates from genome-wide associations, using inverse variance weights under a fixed-effect model in METAL software. Variants yielding a P < 1 × 10⁻⁴ in stage 1 were carried forward to stage 2, and those yielding a P < 1 × 10⁻⁴ in stages 1 and 2 combined were carried forward to stage 3. In stages 2 and 3, sex-adjusted odds ratios (ORs) and their 95% CIs were estimated for each SNP and in each study by means of logistic regression according to an additive model. Associations across stages 1 and 2 studies and across all the studies in stages 1, 2, and 3 were summarized by meta-analyses with Stata version 7.0. The presence of heterogeneity among the 3 studies was tested by means of a χ² statistic. Because this test was not significant for any of the SNPs, we calculated summary ORs according to a fixed-effect model, i.e., by averaging the natural logarithms of the ORs from individual studies, weighted by the inverses of their variances.

The association between rs10911021 and CHD among nondiabetic participants from the NHS and HPFS cohorts was evaluated as described above for diabetic participants. The interaction between rs10911021 and diabetes on CHD risk was evaluated by adding the rs10911021 × diabetes cross-product to a logistic regression analysis of the combined diabetic and nondiabetic NHS/HPFS sets. The same approach was used to evaluate the interaction between rs10911021 and 36 predisposing variants considered in the article by Qi et al.

Power of Genetic Studies
Power for the main SNP effects was estimated with the software CaTS, assuming a risk allele frequency of 0.30. The GWAS of type 2 diabetes participants had 80% power (α = 5 × 10⁻⁶) to detect associations with CHD, with summary ORs across the 3 stages as low as 1.35. The study of rs10911021 in nondiabetic participants had greater than 99% power (α = .05) to detect an association with CHD, with an OR similar to that observed among diabetic participants (OR = 1.26), and 80% power to detect an association with an OR as low as 1.19.

Gene Expression Studies
Change in threshold cycle (ΔCt) values were derived from the threshold cycle (Ct) data for each target gene with the equation ΔCt = Ct (target gene) - Ct (endogenous control). ΔΔCt values were then calculated for each sample and gene as the difference between the ΔCt and the mean ΔCt among rs10911021 T/T homozygotes. For each target gene, the association between rs10911021 and ΔΔCt was evaluated by linear regression with an additive genetic model.

Amino Acid Studies
The association between plasma amino acid levels and rs10911021 genotype or CHD case-control status was evaluated by means of linear regression models, with the amino acid levels as the dependent variables and age, sex, γ-glutamyltransferase levels, rs10911021 genotype, and CHD case-control status as the independent variables. Glutamic acid and the pyroglutamic/glutamic acid ratio were evaluated after log transformation because of their non-normal distributions.

Significance Thresholds
For GWAS analyses, 2-sided P values smaller than 5 × 10⁻⁸ were considered significant; for all other analyses, 2-sided P values smaller than .05 were considered significant.

Results
GWAS and Validations Among Diabetic Participants
A total of 1,517 CHD cases and 2,671 CHD-negative controls, all with type 2 diabetes, were included in the 3-stage genome-wide analyses: 350 cases and 976 controls from the NHS and 319 cases and 665 controls from the HPFS (stage 1), 420 cases and 431 controls from the Joslin Heart Study (stage 2), 314 cases and 384 controls from the Gargano Heart Study—cross-sectional design, and 114 cases and 215 controls from the Canzaro Study (stage 3) (eMethods in the Supplement). The clinical characteristics of the case-control sets analyzed at each stage are summarized in Table 1.

Of the 2,543,016 genetic variants that were tested for association with CHD in stage 1, 26 met the criterion for promotion to stage 2 (P < .001 in stage 1) and 3 of these further met the criterion for promotion to stage 3 (P < .001 in stage 1 + stage 2). Detailed data on the variants associated with CHD at each stage can be found in eTable 1 and eFigures 2 and 3 in the Supplement. Of the 3 variants that were promoted to stage 3, 1 (rs10911021) showed an association with CHD that was nominally significant at each stage and exceeded genome-wide significance in the 3 stages combined (P = 2.0 × 10⁻⁶) (Table 2 and eTable 1 in the Supplement).
In a meta-analysis of the 5 case-control sets, the summary OR of CHD for each copy of the risk allele was 1.36 (95% CI, 1.22-1.51; risk allele frequencies, 0.697 in cases vs 0.696 in controls), with no evidence of heterogeneity across studies ($I^2 = 0\%; P = .82$) (Table 2). The other 2 variants promoted to stage 3 (rs9361923 on chromosome 6 and rs7542837 on chromosome 1) had summary $P$ values across the 5 sets in the $10^{-4}$ range (eTable 1 in the Supplement). None of the loci previously associated with CHD in the general population were among the genetic variants promoted to stages 2 and 3, although 3 of them reached nominal significance at stage 1 (eTable 2 in the Supplement).

### Interaction With Diabetes Status
No association between rs10911021 and CHD was found among 737 nondiabetic CHD cases and 1637 nondiabetic CHD controls (Table 3). The 1 variant with nominally significant association in the general population (rs10911021) lost significance in the diabetes setting. Furthermore, the variant that showed stage 2 association (rs1091021) showed evidence of attenuation in the diabetes setting ($P = .0039$).

### Table 1. Clinical Characteristics of the Discovery and Validation Studies

<table>
<thead>
<tr>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nurses' Health Study</td>
<td>Joslin Heart Study</td>
<td>Gargano Heart Study</td>
</tr>
<tr>
<td>Cases</td>
<td>Controls</td>
<td>Cases</td>
</tr>
<tr>
<td>No. of participants</td>
<td>350</td>
<td>976</td>
</tr>
<tr>
<td>Age, mean (SD), y</td>
<td>46 (6)</td>
<td>46 (7)</td>
</tr>
<tr>
<td>Male</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Diabetes duration, mean (SD), y</td>
<td>14 (8.7)</td>
<td>14 (9.4)</td>
</tr>
</tbody>
</table>

### Table 2. Association Between rs10911021 and CHD in the Presence of Type 2 Diabetes in 5 Independent Studies

<table>
<thead>
<tr>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nurses' Health Study</td>
<td>Joslin Heart Study</td>
<td>Gargano Heart Study</td>
</tr>
<tr>
<td>Risk allele</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>RAF controls</td>
<td>0.679</td>
<td>0.680</td>
</tr>
<tr>
<td>RAF cases</td>
<td>0.735</td>
<td>0.760</td>
</tr>
<tr>
<td>$P$ value for HWE</td>
<td>.69</td>
<td>.66</td>
</tr>
<tr>
<td>Odds ratio (95% CI)</td>
<td>1.36 (1.19-1.69)</td>
<td>1.50 (1.21-1.87)</td>
</tr>
<tr>
<td>$P$ value for association</td>
<td>.0059</td>
<td>.0003</td>
</tr>
<tr>
<td>$P$ value for heterogeneity</td>
<td>.24</td>
<td>.10</td>
</tr>
</tbody>
</table>

### Abbreviations:
- HWE: Hardy-Weinberg equilibrium; RAF: risk allele frequency.
- $P$ value for HWE in the control groups.
- OR = 1.49; 95% CI, 1.20-1.86; and $P = .0004$ after adjustment for top principal components.
- *Baseline age for Nurses’ Health Study (NHS) and Health Professionals Follow-up Study (HPFS); age of enrollment for the other studies.
- Diabetes duration at coronary heart disease event (cases) or censoring (controls) for NHS and HPFS; diabetes duration at enrollment for the other studies.

In a meta-analysis of the 5 case-control sets, the summary OR of CHD for each copy of the risk allele was 1.36 (95% CI, 1.22-1.51; risk allele frequencies, 0.697 in cases vs 0.696 in controls), with no evidence of heterogeneity across studies ($I^2 = 0\%; P = .82$) (Table 2). The other 2 variants promoted to stage 3 (rs9361923 on chromosome 6 and rs7542837 on chromosome 1) had summary $P$ values across the 5 sets in the $10^{-4}$ range (eTable 1 in the Supplement). None of the loci previously associated with CHD in the general population were among the genetic variants promoted to stages 2 and 3, although 3 of them reached nominal significance at stage 1 (eTable 2 in the Supplement).
negative controls from the NHS and HPFS cohorts (eTable 3 in the Supplement). The OR among these nondiabetic individuals was not significantly different from 1 (OR = 0.99; 95% CI, 0.87-1.13; P = .89; risk allele frequencies, 0.697 in cases vs 0.696 in controls) while being significantly different from the OR in diabetic participants (OR = 1.36; 95% CI, 1.22-1.51; P = for diabetes × genetic variant interaction, 2.6 × 10⁻⁴). Among the NHS and HPFS diabetic participants, no significant interaction on CHD risk was observed between rs10911021 and established type 2 diabetes–predisposing variants, considered individually or in combination as a genetic predisposition score.29 The −2 ΔΔCT value is a measure of the messenger RNA level in each endothelial cell line normalized to the average messenger RNA level in T/T homozygous lines.

The expression of GLUL, the closest gene in telomeric direction, was significantly associated with rs10911021 in endothelial cells, being 32% lower in risk allele (C/C) homozygotes compared with protective allele (T/T) homozygotes, with heterozygotes having intermediate levels (P for trend = .0048). ZNF648, the closest gene on the 5′ side, was not expressed in endothelial cells and none of the other neighboring genes were significantly associated with rs10911021.

### Association With Plasma Markers of Glutamic Acid Metabolism and the γ-Glutamyl Cycle

In a sample of 100 Joslin Heart Study participants, no significant differences in plasma glutamic acid or glutamine (the substrate and the product, respectively, of the enzyme encoded by GLUL) were observed between risk allele C homozygotes and allele T homozygotes (Table 4). However, the ratio between plasma pyroglutamatic acid (the immediate precursor of glutamic acid in the γ-glutamyl cycle) and glutamic acid was significantly lower in C/C as compared to T/T carriers (P = .03) (Table 4). In this sample, the pyroglutamatic-to-glutamic ratio was also significantly lower in the 44 participants who had developed CHD (median = 0.79; interquartile range 0.62-0.97) than in the 56 who were CHD negative (median, 0.92; interquartile range, 0.78-1.14) (P = .02). The OR of CHD for the rs10911021 C/C genotype in this subsample decreased from 1.83 to 1.39 (≈50% reduction in the log scale) after adjustment for the pyroglutamatic-to-glutamic acid ratio, suggesting that the effect of this locus on CHD was at least in part mediated by its effect on this parameter.

### Genotype Association With the Expression of Neighboring Genes

Variant rs10911021 is located between 2 genes, ZNF648 (~51 kb in centromeric direction; NCBI Entrez Gene 127665) and GLUL (~270 kb in telomeric direction; NCBI Entrez Gene NG_013347.1), and neighbors several other genes (eFigure 1 in the Supplement). No missense variants in linkage disequilibrium with rs10911021 were identified in the HapMap or the 1000 Genome Projects databases, suggesting an effect on gene regulation as the mechanism underlying the observed association with CHD. In support of this hypothesis, rs10911021 is listed in the Regulome DB as occurring in an E-box binding site for basic helix-loop-helix transcription factors, and ENCODE data indicate that a variant in linkage disequilibrium with this variant (rs7517310; r² = 0.72 in the HapMap database) is placed in a high DNase I sensitivity cluster binding to the RE1-silencing transcription factor in a variety of cell types. As shown in Table 3, the expression of GLUL, the closest gene in telomeric direction, was significantly associated with rs10911021 in endothelial cells, being 32% lower in risk allele (C/C) homozygotes compared with protective allele (T/T) homozygotes, with heterozygotes having intermediate levels (P for trend = .0048). ZNF648, the closest gene on the 5′ side, was not expressed in endothelial cells and none of the other neighboring genes were significantly associated with rs10911021.

### Table 3. Endothelial Cell Expression of Genes Adjacent to rs10911021 According to the Genotype at This Locus

<table>
<thead>
<tr>
<th>Gene</th>
<th>Location</th>
<th>Position (Mb)</th>
<th>T/T (n = 16)</th>
<th>C/T (n = 42)</th>
<th>C/C (n = 60)</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR1</td>
<td>Centromeric</td>
<td>179.27-179.2</td>
<td>1.00 (0.74-1.35)</td>
<td>0.76 (0.60-0.96)</td>
<td>0.76 (0.66-0.88)</td>
<td>.24</td>
</tr>
<tr>
<td>IER5</td>
<td>Centromeric</td>
<td>179.32-179.33</td>
<td>1.00 (0.66-1.51)</td>
<td>0.98 (0.82-1.18)</td>
<td>0.90 (0.82-1.00)</td>
<td>.39</td>
</tr>
<tr>
<td>CACNA1E</td>
<td>Centromeric</td>
<td>179.72-180.04</td>
<td>UD</td>
<td>UD</td>
<td>UD</td>
<td></td>
</tr>
<tr>
<td>ZNF648</td>
<td>Centromeric</td>
<td>180.29-180.30</td>
<td>UD</td>
<td>UD</td>
<td>UD</td>
<td></td>
</tr>
<tr>
<td>GLUL</td>
<td>Telomeric</td>
<td>180.62-180.63</td>
<td>1.00 (0.62-1.62)</td>
<td>0.81 (0.71-0.92)</td>
<td>0.68 (0.62-0.76)</td>
<td>.0048</td>
</tr>
<tr>
<td>TEDDM1</td>
<td>Telomeric</td>
<td>180.63-180.64</td>
<td>1.00 (0.34-2.95)</td>
<td>1.11 (0.77-1.61)</td>
<td>1.01 (0.75-1.37)</td>
<td>.90</td>
</tr>
<tr>
<td>LIN60272</td>
<td>Telomeric</td>
<td>180.61-180.68</td>
<td>UD</td>
<td>UD</td>
<td>UD</td>
<td></td>
</tr>
<tr>
<td>RGS1</td>
<td>Telomeric</td>
<td>180.69-180.80</td>
<td>UD</td>
<td>UD</td>
<td>UD</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviation: UD, undetectable.

*Data are geometric means (95% CI) of the −2 ΔΔCT values obtained by real-time polymerase chain reaction. The −2 ΔΔCT value is a measure of the messenger RNA level in each endothelial cell line normalized to the average messenger RNA level in T/T homozygous lines.

### Table 4. Plasma Glutamine, Glutamic Acid, and Pyroglutamic/Glutamic Acid Ratio According to rs10911021 Genotype

<table>
<thead>
<tr>
<th>Metabolite</th>
<th>T/T (n = 49)</th>
<th>C/C (n = 49)</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glutamine, μmol/L</td>
<td>501 (417-568)</td>
<td>519 (463-573)</td>
<td>.30</td>
</tr>
<tr>
<td>Glutamic acid, μmol/L</td>
<td>111 (91-138)</td>
<td>115 (102-132)</td>
<td>.18</td>
</tr>
<tr>
<td>Pyroglutamic/glutamic acid</td>
<td>0.94 (0.76-1.14)</td>
<td>0.79 (0.67-0.98)</td>
<td>.029</td>
</tr>
</tbody>
</table>

Abbreviation: IQR, interquartile range.
Association With Other Cardiovascular Risk Factors
No significant association between rs10911021 and serum fasting insulin, homeostatic assessment model insulin-resistance index, or 2-hour glucose during an oral glucose tolerance test was found in the MAGIC database including data on more than 35,000 nondiabetic individuals. Similarly, no significant association was found with type 2 diabetes in the DIAGRAM database (OR = 1.01; 95% CI, 0.97-1.04; P = .76).

Discussion
In this study, we have identified a previously unknown genetic locus associated with increased CHD risk among type 2 diabetic patients. The locus is in the region of the GLUL gene on chromosome 1q25 and may affect CHD risk by reducing the expression of this gene and affecting glutamate and glutamine metabolism in endothelial cells. This genetic variant appeared to be specifically associated with CHD in the diabetic population and showed a significant gene-by-disease synergism on CHD risk.

Several pieces of evidence suggest that these findings are unlikely to be due to chance. First, the P value for the association between this locus and CHD in type 2 diabetes participants meets genome-wide significance (P < 5 × 10^{-8}), namely, withstands adjustment for the large number of comparisons that are made in a genome-wide analysis. Second, the association was consistent across multiple samples of type 2 diabetic participants of different ethnic and geographic origin, reaching nominal significance in 4 of the 5 sets that were considered. Third, the difference in ORs between diabetic and nondiabetic participants was supported by a robust P value for interaction. Finally, an association between this locus and CHD was also found in a large study of the general population (CARDIoGRAM) with a magnitude similar to what one would expect according to the effects detected in our study in diabetic and nondiabetic participants and the prevalence of diabetes in CARDIoGRAM.

GLUL, the gene whose expression is decreased in risk allele carriers, encodes glutamate-ammonia ligase (also known as glutamine synthase), which catalyzes the conversion of glutamic acid and ammonia into glutamine. Both amino acids play important roles in human physiology. Glutamic acid is a key intermediate of several metabolic pathways, most notably of the γ-glutamyl cycle, through which the antioxidant glutathione is generated; glutamine is involved in the regulation of cell proliferation, inhibition of apoptosis, and cell signaling. Evidence from experimental and human studies points to glutamine/glutamic acid metabolism as contributing to the regulation of insulin secretion and glucose metabolism. In islets, glutamine enhances both mitochondrial metabolism and insulin secretion. In diabetic patients, it was found that glutamine reduced glucose excursions when administered before oral glucose and effectively increased circulating incretin and insulin concentrations. Several clinical trials also suggest cardioprotective effects of glutamine used parenterally and enteraly. In epidemiologic studies, abnormal metabolism of these amino acids has been shown to be related to insulin resistance, type 2 diabetes, and cardiovascular disorders.

The mechanisms through which alterations of glutamate and glutamine metabolism, such as those that one would expect from the reduced GLUL expression observed in risk allele carriers, may lead to increased CHD risk are unclear. The newly identified CHD risk variant was not associated with risk of type 2 diabetes in DIAGRAM, suggesting that the pathways underlying the association with CHD are distinct from those involved in the etiology of type 2 diabetes. Similarly, the absence of association between the risk variant and serum fasting insulin, homeostatic assessment model insulin-resistance index, or 2-hour glucose during an oral glucose tolerance test in the MAGIC database seems to exclude insulin resistance as the underlying mechanism.

Rather, our finding of association between the risk variant and a lower pyroglutamico-to-glutamic acid ratio in plasma and the fact that the association between risk allele and CHD was attenuated after adjustment for this variable suggest an impairment of the γ-glutamyl cycle, of which pyroglutamic acid is an intermediate, as a possible mechanism. Such alteration might increase CHD risk by limiting the availability of the natural antioxidant glutathione, compound the known negative effect of diabetes on this metabolite and potentially explaining the fact that this genetic effect can be observed only among diabetic participants. Consistent with this hypothesis, an association between rs10911021 and pyroglutamine (expressed as the ratio with the fatty acid sebacate) is also found in the KORA/Twins UK metabolomic databases (P = .00096 in KORA; http://metabolomics.helmholtz-muenchen.de/gwa). However, additional contributions by pathways that are not directly related to glutamate and glutamine may also be present because other metabolites implicated in vascular biology and atherogenesis, such as the long-chain ω3-polyunsaturated fatty acid eicosapentænoate (20:5n3) and a variety of lysophospholipids, are associated with rs10911021 in those same databases.

Further studies are needed to dissect the mechanisms linking this locus to the development and progression of atherosclerosis in diabetes. As part of these efforts, it would be useful to extend the study to type 1 diabetes because this may provide clues about whether the gene × diabetes interaction involves hyperglycemia or instead concerns factors that are specific to type 2 diabetes, such as insulin resistance or some of the genes predisposing to this form of diabetes. However, the lack of interaction in our study between rs10911021 and genetic variants predisposing to type 2 diabetes makes the latter hypothesis unlikely.

Our study has several strengths, namely, the validation design with 5 independent cohorts of diabetic patients, a rigorous definition of CHD, and a sample size that was adequate for the detection of additive genetic effects of the magnitude reported. Nonetheless, some limitations should be acknowledged. First, although our study was powered to detect major genetic effects such as that described in this article, larger studies would be necessary to detect loci having smaller but still relevant effects on CHD risk in diabetes. In this context, the use of analytic methods based on biological pathways such as gene ontology might lead to the identification of additional genetic determinants of CHD in diabetic patients and pro-
vide further insights on the links between diabetes and atherogenesis. Second, our study was restricted to non-Hispanic whites, and whether these findings can be generalized to other races remains to be determined. Also, according to the known differences in linkage disequilibrium patterns among races, different genetic markers may be more effective in capturing the predisposing effect of the locus described in this article in other racial groups. Third, although the achieved level of statistical significance meets genome-wide significance, it still corresponds to a 5% probability of a false-positive result. Although the likelihood of such an event is reduced by the validation of the association in CARDIoGRAM, further studies are needed before this CHD locus can be considered as fully validated.

**Conclusion**

In summary, through a 3-stage GWAS in 4188 type 2 diabetic patients, we have identified a novel susceptibility locus for CHD in the region of the GLUL gene. This locus appears to be associated with CHD very weakly or not at all among nondiabetic participants, consistent with a gene × diabetes synergism. Preliminary evidence suggests that this locus may modulate CHD risk by affecting glutamate/glutamine metabolism and the activity of the γ-glutamyl cycle, but further studies are needed to fully understand the biological mechanisms linking it to CHD in diabetes.

**ARTICLE INFORMATION**

**Author Affiliations:** Department of Nutrition, Harvard School of Public Health, Boston, Massachusetts (L.Qi, Q.Qi, Rimm, Hu); Channing Division of Network Medicine, Department of Medicine, Brigham and Women’s Hospital and Harvard Medical School, Boston, Massachusetts (L.Qi, Rimm, Hu); ICRSS Casa Sollevo della Sofferenza-Mendel Laboratory, San Giovanni Rotondo, Italy (Prudente, Trischitta); Research Division, Joslin Diabetes Center, Boston, Massachusetts (Mendonca, Novelli, Mannino, Niewczas, Krolewski, Doria); Department of Medical and Surgical Sciences, University Magna Gracia, Catanzano, Italy (Andreozzi, Mannino, Sesti); Department of Experimental and Clinical Sciences, University “G. d’Annunzio,” Aging Research Center, “G. d’Annunzio” University Foundation, Chieti-Pescara, Italy (di Pietro, Pandolfi); Department of Medical, Surgical and Health Sciences, University of Trieste, Italy (Sturma, Biolo); Department of Medicine, Harvard Medical School, Boston, Massachusetts (Novelli, Gervino, Hauser, Muehlischlégel, Niewczas, Krolewski, Doria); Department of Medicine and Aging Sciences, University “G. d’Annunzio,” Aging Research Center, “G. d’Annunzio” University Foundation, Chieti-Pescara, Italy (Formoso); Cardiovascular Division, Beth Israel Deaconess Medical Center, Boston, Massachusetts (Gervino, Hauser); Department of Anesthesiology, Perioperative and Pain Medicine, Brigham and Women’s Hospital, Boston, Massachusetts (Muehlischlégel); Research Unit of Diabetes and Endocrine Diseases, ICRSS Casa Sollevo della Sofferenza, San Giovanni Rotondo, Italy (Trischitta); Department of Experimental Medicine, Sapienza University, Rome, Italy (Trischitta).

**Author Contributions:** Drs Q. Qi and Doria had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis. Study concept and design: Trischitta, Hu, Doria, L.Qi. Acquisition of data: Q. Qi, Prudente, Mendonca, Andreozzi, di Pietro, Novelli, Mannino, Formoso, Hauser, Muehlischlégel, Niewczas, Krolewski, Pandolfi, Rimm, Sesti, Trischitta, Doria, L.Qi. Analysis and interpretation of data: Q. Qi, Prudente, Andreozzi, Sturma, Novelli, Mannino, Gervino, Hauser, Niewczas, Krolewski, Biolo, Sesti, Trischitta, Hu, Doria, L.Qi. Drafting of the manuscript: Q. Qi, Trischitta, Doria, L.Qi.

**Critical revision of the manuscript for important intellectual content:** Q. Qi, Prudente, Mendonca, Andreozzi, di Pietro, Sturma, Novelli, Mannino, Formoso, Gervino, Hauser, Muehlischlégel, Niewczas, Krolewski, Biolo, Pandolfi, Rimm, Sesti, Hu, L.Qi. Statistical analysis: Q. Qi, Niewczas, Doria, L.Qi. Obtained funding: Rimm, Trischitta, Doria, L.Qi. Administrative, technical, or material support: Prudente, Mendonca, Andreozzi, Sturma, Novelli, Mannino, Gervino, Hauser, Muehlischlégel, Sesti, Hu, L.Qi. Study supervision: Krolewski, Pandolfi, Trischitta, Doria, L.Qi. Drs L.Qi and Doria contributed equally to this work and are co–senior authors.

**Conflict of Interest Disclosures:** All authors have completed and submitted the ICJME Form for Disclosure of Potential Conflicts of Interest. Dr L.Qi reported serving as a consultant to Genovive. Dr Hauser reported serving as a consultant to Astellas and the Harvard Clinical Research Institute. Dr Krolewski reported receiving honoraria from Merck, Eli Lilly, and Boehringer Ingelheim. Dr Biolo reported receiving payment for lectures from Baxter and Fresenius Kabi. Dr Sesti reported serving as a consultant to Novo Nordisk, Merck, Servier, Boehringer Ingelheim, and sanofi and serving on the speakers bureau for Novartis. Novo Nordisk, Bristol-Myers Squibb, and Laboratori Guidotti. Dr Hu reported serving as a consultant to Novo Nordisk and his institution received a grant from Merck. Dr Doria reported that his institution received a grant from sanofi-aventis.

**Funding/Support:** This study was supported by grants HL071981, DK091718, HL073168, DK046200 (Boston Obesity Nutrition Research Center), and DK68336 (Genetics Core of the Diabetes Research Center at the Joslin Diabetes Center) from the National Institutes of Health, an American Heart Association Scientist Development Award (0730094N), a grant from the Italian Ministry of Health (“Ricerca Corrente 2011 e 2012”), and a grant from Fondazione Roma (“Sostegno alla ricerca scientifica biomédica 2008”). A portion of this work was conducted in a facility constructed with support from the National Institutes of Health Research Facilities Improvement Program (RR16000-01, CA62528-01, RR14534-01) from the National Center for Research Resources.

**Role of the Sponsors:** The funding agencies had no role in the design and conduct of the study; collection, management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; or decision to submit the manuscript for publication.

**Additional Contributions:** We thank all the participants of the study and CARDIoGRAM for providing data on the association between variants in the rs10911021 region and CHD in the general population. Data on glycemic traits were contributed by MAGIC investigators and downloaded from http://www.magicinvestigators.org. Data on type 2 diabetes were contributed by DIAGRAM investigators and downloaded from http://diagram-consortium.org.

**REFERENCES**

Glutamic Acid Metabolism Variant and CHD in Diabetes


