Variants in Scavenger Receptor Class B Type I Gene Are Associated with HDL Cholesterol Levels in Younger Women

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Abstract
Objective: Variants within the scavenger receptor class B type I (SCARB1) receptor gene have been previously associated with lipid levels, especially in women, with some studies reporting the association to be stronger in the presence of diabetes or post-menopausal estrogen use. Based on the reported gender-specific association and modification effect of estrogen on lipid levels according to SCARB1 variants, we explored the relationship between SCARB1 single nucleotide polymorphisms (SNPs) and lipid levels in an Amish population to assess sex and age differences. Methods: Eight SCARB1 SNPs, identified from public databases, were genotyped in 919 subjects. Results: Rs5888 and rs3782287 were in high linkage disequilibrium (LD), with \( r^2 > 0.8 \). None of the SNPs were significantly associated with lipid levels in men; however in women, rs5888 (\( p = 0.04 \)) and rs5891 (\( p < 0.001 \)) were significantly associated with higher HDL-C levels. Rs5891 had an allele frequency of 3% and predicts a missense mutation (Ile135Val), which may be functional. Moreover, rs3782287 (\( p = 0.023 \)) and rs5888 (\( p = 0.003 \)) were significantly associated with higher HDL-C levels in women younger than 50 years but not in women aged 50 years or older (\( p \) for interaction between age and rs5888 = 0.045).

None of the SNP effects on HDL-C were modified in the presence of diabetes, in either men or women. Conclusions: SCARB1 SNPs influence HDL-C levels in women, particularly in those less than 50 years old. Condensed Abstract: We assessed associations between SCARB1 SNPs and lipid traits in 919 Amish men and women. Two SNPs, rs3782287 and rs5888, were significantly associated with higher HDL-C levels in women younger than 50 years but not in women aged 50 years or older, supporting an interaction between common sequence variants in SCARB1 and estrogen on HDL-C.

C.G.P. Roberts and H. Shen are co-first authors.

The metabolism of high-density lipoprotein (HDL) is complex, with many factors influencing its circulating plasma levels. One such factor is the scavenger receptor, class B, type I (SR-BI), first characterized by Acton et al. [1], and subsequently shown to be a physiologically relevant receptor that exerts a major influence on HDL cho-

lesterol (HDL-C) levels in rodents [2]. It is highly expressed in the liver and in steroidogenic tissues [1, 3], where its primary function is to mediate the uptake of cholesteryl esters from the HDL particle core.

Much less is known regarding the role of SR-BI in humans, although recent studies have shown some variants in the SR-BI gene (SCARB1) to be associated with lipid levels, lipoprotein particle size and body mass index (BMI) [4–8]. SCARB1 variants have also been studied in populations characterized with type 2 diabetes mellitus (T2DM) [5, 9] and, interestingly, a SCARB1 variant in exon 1 was found to associate with differences in insulin sensitivity in healthy people during the consumption of an olive oil-rich diet [10]. In addition, a SCARB1 variant was studied in older women using hormone replacement therapy [11]. Osgood et al. [9] examined SCARB1 gene variants in the participants of the Framingham Study, and reported that three common single nucleotide polymorphisms (SNPs) rs4238001 (exon 1, +4 G → A), rs5888 (exon 8, +63519 C → T) and an intron 5 (+51905 C → T) SNP were associated with variation in plasma lipoprotein concentrations and particle size, particularly in subjects with T2DM. While there was no association of SNPs with T2DM, the G allele in rs4238001 was significantly associated with lower HDL-C levels and smaller HDL particle sizes, although only among subjects with T2DM. No interaction was observed for the rs5888 SNP with T2DM, whereas the interaction between the intron 5 SNP and T2DM on HDL metabolism was seen only in men.

Gender-specific associations have been reported between some of the SCARB1 variants and lipid levels, an observation that led Richard et al. [11] to examine the effect of exogenous estrogen on HDL-C levels by SCARB1 variants in elderly women in the Rancho Bernardo Study. These investigators found no significant associations between either the intron 5 SNP or rs5888 and HDL-C levels after adjusting for age, BMI, alcohol, smoking, triglycerides, fasting plasma glucose and estrogen use. However, they did report significant estrogen interaction with the rs5888 SNP on HDL-C levels, with HDL-C levels significantly higher in estrogen users than non-users [11].

Motivated by these previous observations, we assessed the relationship of eight different SCARB1 variants, including the previously studied rs4238001, intron 5 (+51905 C → T), and rs5888 variants, with lipid levels in adult men and women participants of the Amish Family Diabetes Study (AFDS) and to determine if associations were modified by the effects of age, gender and/or T2DM.

### Methods

#### Study Population

The Old Order Amish (OOA) is a genetically homogenous population of Central European ancestry. The original founders of this population immigrated to eastern Pennsylvania (now Lancaster County, PA, USA) in the mid to late 1700s, with the Lancaster County population now consisting of approximately 30,000 individuals [12]. The OOA today are still characterized by their social cohesiveness and rural lifestyle [13]. In 1995, AFDS was begun to identify susceptibility genes for T2DM and related traits. Proband with T2DM onset between 35 and 65 years of age were identified and all willing first-degree family members 18 years of age and older were invited to participate. First-degree relatives of any family members subsequently diagnosed with T2DM were also invited to participate. A total of 919 subjects with lipid data and DNA available for genotyping were included in this study.

Participating subjects were examined at the Amish Research Clinic in Strasburg, PA following a 12-hour overnight fast. Height and weight were measured and body mass index (BMI) was calculated as the weight in kilograms divided by the height in meters squared (kg/m²). Fasting lipid profiles [total cholesterol (TC), HDL-C, triglycerides (TG)] were performed by Quest Diagnostics (Baltimore, MD). Intra-assays CVs of duplicate samples ranged between 0.1 and 3.0%, and inter-assay CVs ranged between 0.2 and 5%. Low-density lipoprotein cholesterol (LDL-C) concentrations were estimated using Friedewald’s formula [14].

A 75 g oral glucose tolerance test (OGTT) was administered and diabetes mellitus was classified based on the American Diabetes Association plasma glucose criteria [15] of a fasting plasma glucose level (≥7 mmol/l) or a 2-hour OGTT plasma glucose level (≥11.1 mmol/l). Subjects were also considered to have diabetes if they reported current use of insulin or oral glucose-lowering agents. Subjects were excluded from these analyses if they had a diagnosis of diabetes before the age of 35 years and reported current use of insulin (n = 1). Impaired glucose tolerance was diagnosed based on OGTT plasma glucose levels (2-hour OGTT plasma glucose level ≥7.8 but <11.1 mmol/l). Normal glucose tolerance was defined as fasting plasma glucose level (<6.1 mmol/l) and 2-hour OGTT plasma glucose level (<7.8 mmol/l).

Informed consent was obtained from all AFDS participants, and the study protocol was approved by the Institutional Review Board at the University of Maryland School of Medicine. Details of the study design have been previously described [13].

#### Genotyping

The SCARB1 gene is 93.2 kb in length and consists of 13 exons. We selected SNPs for genotyping within the coding and intronic regions of SCARB1 from public databases (NIH dbSNP, Wellcome Trust Sanger Institute and Applied Biosystems) that were validated by frequency (minor allele frequency ≥1%) as well as SNPs reported in published articles [4–8, 16]. SNPs were genotyped using the SNPstream UHT Genotyping System (Beckman Coulter, Fullerton, CA) [17]. Eight of the eighteen SNPs genotyped were polymorphic in this sample: rs3782287, rs5888, rs5890, rs5891, rs838884, rs10846760, rs10846745, rs11057851 and the intron 5 (+51905 C → T) SNP. Error rates based upon blind replicates were 0–4.7%.
Statistical Analysis

Genotypes were checked for Mendelian consistency using the PedCheck software program in the extended Amish pedigree [18]. A small number of Mendelian errors were resolved or removed prior to analysis. The distribution of all SNP genotypes conformed to those expected under Hardy-Weinberg equilibrium using the $\chi^2$ test.

Association analyses were performed using a variance components methodology implemented in the Sequential Oligogenic Linkage Analysis Routines (SOLAR) software program, which allowed us to account for the relatedness of study subjects [19]. Briefly, we evaluated the effects of SNP genotype on HDL levels, while simultaneously adjusting for the effects of age, age$^2$, sex, BMI, and diabetes status. We accounted for the non-independence among family members by modeling the residual correlations in HDL levels between relative pairs explicitly as a function of the kinship matrix. Our primary analysis was based on an additive genetic model, which implies a dose-response relationship between number of 'risk' alleles and HDL level. Genotypes were thus assigned values of 0, 1, or 2, corresponding to the number of risk alleles. Subjects currently taking lipid-lowering medications (n = 14) were excluded from the analysis. The significance of the genotype effects was assessed using the likelihood ratio test, in which we compared the likelihood of the data under a model in which the genotype effect was estimated against the likelihood of a nested model in which the genotype effect was constrained to zero.

Based upon our a priori hypothesis regarding an interaction between SCARB1 genotype and age or sex, genotype-phenotype associations were estimated in men and women (and older and younger women) separately. Interaction terms (e.g., genotype by sex, genotype by diabetes status, and genotype by age) were included in the model to assess whether the magnitude of the genotype effect on HDL levels differed by group.

Given negligible LD between SNPs (except rs5888 and rs3782287), haplotypes could not be reliably assigned, and thus haplotype association analysis was not performed.

### Results

The 919 study subjects included 103 T2DM and 816 non-T2DM individuals from 226 families, ranging in size from 1 to 169. The characteristics of the study cohort are summarized in table 1. Overall, there were slightly more women than men (53 vs. 47%). Women had higher BMI (27.9 vs. 26.3 kg/m$^2$, $p < 0.0001$), higher prevalence of T2DM (14.2 vs. 9.8%, $p < 0.043$), higher mean HDL-C levels (53.9 vs. 46.9 mg/dl, $p < 0.0001$) and lower mean LDL-C levels (143.0 vs. 149.6 mg/dl, $p < 0.013$). The use of prescription medications such as lipid-lowering agents and hormone replacement therapy is low in the Amish. The frequency of cigarette smoking is also low in the Amish. Physical activity levels in the Old Order Amish are typically high, especially compared to non-Amish Caucasians. The Amish diet is generally high in calories and fat.

We next examined the associations between SCARB1 SNPs and lipid levels stratified by sex. In these analyses, we adjusted for age, age$^2$, BMI, diabetes status, family structure and excluded those using lipid-lowering medications. None of the SCARB1 SNPs were associated with TC, HDL-C, LDL-C, or TG levels in men (data not shown). However, in women, rs5888 (p = 0.04) and rs5891 (p < 0.001) were significantly associated with higher HDL-C levels (53.9 vs. 46.9 mg/dl, p < 0.0001) and lower mean LDL-C levels (143.0 vs. 149.6 mg/dl, p < 0.013). The use of prescription medications such as lipid-lowering agents and hormone replacement therapy is low in the Amish. The frequency of cigarette smoking is also low in the Amish. Physical activity levels in the Old Order Amish are typically high, especially compared to non-Amish Caucasians. The Amish diet is generally high in calories and fat.

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associations between SCARB1 SNPs and HDL-C levels in women older and younger than age 50 years. As shown in table 2, women less than 50 years of age who carried the rs5888 (p < 0.003) or rs3782287 (p < 0.023) minor allele had significantly higher HDL-C levels compared with women homozygous for the major allele (HDL-C levels approximately 13 and 9% higher, respectively). In women greater than 50 years of age, these two SNPs were not associated with HDL-C levels. The genotype × age group interaction term was statistically significant for rs5888 genotypes (p = 0.045). By contrast, rs5891, which encodes a missense mutation (Ile135Val), was associated with HDL-

![Fig. 1. Gene structure and pairwise LD among SNPs in SCARB1. The upper portion of the figure shows the gene structure and location of polymorphisms. The lower portion of the figure shows a schematic pairwise LD, calculated as D' and r² among the polymorphic SNPs in the Amish. The lines connect each SNP name and the position with the corresponding cell in the LD matrix. Magnitude and significance of the D' and r² is illustrated by shading with a red to white or a blue to white gradient reflecting higher to lower LD values.](image)

<table>
<thead>
<tr>
<th>SNP name</th>
<th>MAF</th>
<th>Women ≥50 years (n = 192): Genotype</th>
<th>Women &lt;50 years (n = 293): Genotype</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>rs10846760 (C/T)</td>
<td>0.25</td>
<td>54.4 (6.4)</td>
<td>55.6 (6.4)</td>
</tr>
<tr>
<td>rs11057851 (G/A)</td>
<td>0.08</td>
<td>55.1 (1.5)</td>
<td>59.4 (2.7)</td>
</tr>
<tr>
<td>rs5890 (C/T)</td>
<td>0.003</td>
<td>54.9 (12.5)</td>
<td>63.4 (12.4)</td>
</tr>
<tr>
<td>rs5891 (G/A)</td>
<td>0.03</td>
<td>54.6 (1.4)</td>
<td>65.5 (4.2)</td>
</tr>
<tr>
<td>Intron5 (T/C)</td>
<td>0.05</td>
<td>55.5 (1.4)</td>
<td>54.2 (2.9)</td>
</tr>
<tr>
<td>rs3782287 (A/G)</td>
<td>0.41</td>
<td>54.3 (2.8)</td>
<td>57.1 (2.6)</td>
</tr>
<tr>
<td>rs5888 (C/T)</td>
<td>0.41</td>
<td>53.3 (2.7)</td>
<td>56.9 (2.5)</td>
</tr>
<tr>
<td>rs838884 (T/C)</td>
<td>0.23</td>
<td>56.2 (1.6)</td>
<td>54.7 (1.9)</td>
</tr>
</tbody>
</table>

* p is for additive genetic model, adjusted for age, BMI, family structure, diabetes, and excluded lipid medications. Significant p values are printed in bold.
C levels in women from both age groups, although this SNP was uncommon (3%) in this population. None of the SNPs were associated with diabetes, in either men or women, nor were the effects of any SNP on HDL-C levels modified in the presence of diabetes. Excluding subjects with diabetes did not appreciably change the HDL-C association results (data not shown).

A description of the gene structure showing SNP locations and pairwise LD between SNPs is provided as figure 2. Rs5888 (exon 8; silent) and rs3782287 (intron 7), both of which were associated with HDL-C levels in women younger than 50 years old, are located 4.5 kb from each other and are in high LD with each other. By contrast, rs5891 (exon 3; Ile135Val), which was also associated with HDL-C levels, is rarer and not linked to the other two HDL-C-associated SNPs, suggesting that its association with HDL-C levels is independent of the other two SNPs. This was supported by the fact that the association of rs5891 with HDL-C levels remained statistically significant even after adjusting for the effects of the other two SNPs in either total women or women of each age group. The opposite analyses were done on rs5888 or rs3782287 while adjusting for rs5891. Significant association between rs5888 or rs3782287 and HDL-C remained in total women and women younger than 50 years old (data not shown). Because of the relative absence of LD between all pairs of SNPs ($r^2 \leq 0.20$), with the exception of SNPs rs5888 and rs3782287, which were in very high LD ($r^2 = 0.86$), no haplotype association analyses were performed.

**Discussion**

We have observed several SCARB1 polymorphisms to be associated with HDL-C levels in Amish women, but not in men. Furthermore, the associations were stronger in younger as compared to older women. Because Amish women, at least in Lancaster County, rarely take estrogen (0.41% in our cohort), the stratification of women according to those younger and older than age 50 years is a proxy for examining the interaction of estrogen on lipid levels according to SCARB1 genotype. Our results are consistent with Richard et al. [11] in that HDL-C levels were significantly higher in Amish women younger than 50 years of age (presumably pre-menopausal and having adequate endogenous estrogen levels) who carried the rs5888 variant, suggesting an important interaction between estrogen and SR-BI. In addition, we found significantly higher HDL-C in younger female carriers of the minor allele of rs3782287. However, unlike the Rancho Bernardo population, we did not find a difference in LDL-C levels in the Old Order Amish women according to age and SCARB1 genotype.

Osgood et al. [9] did not show a sex difference between lipid levels and the rs5888 SNP. After multivariate adjustments, they showed that men homozygous for the minor allele had significantly higher total HDL-C, higher HDL$_3$-C levels and larger HDL particle size compared with men homozygous for the major allele. However, in women, while there were no apparent differences in HDL-C levels between minor allele homozygotes and major allele homozygotes, LDL-C levels were lower and HDL particle size was larger in the minor allele homozygotes [9]. Acton et al. [4] also did not find significant as-
associations between lipid levels and the rs5888 SNP in men in a population sampled from Zaragoza, Spain. While they also did not find significant associations between HDL-C levels and rs5888 variant in women, they report-
ed that women carrying the minor allele had significantly
lower LDL-C levels compared to women homozygous for
the major allele. Other groups examining the rs5888
SNP have also reported association of this SNP with lipid
levels [5, 6]. Thus, our findings, coupled with reports in
the literature, provide evidence for replicated association
of rs5888 with lipid levels, although there appear to be
inconsistencies with respect to which lipid traits.

In our population we did not find associations be-
tween SCARBI SNPs and triglycerides (p ranges 0.08–
0.8). Only one SCARBI SNP was significantly associated
with BMI (rs5891, p = 0.04). Relationships between BMI,
triglycerides, and SCARBI SNPs have been found in a
Spanish population [4], and relationships between tri-
glycerides and the SCARBI intron 5 SNP have been de-
scribed in an obese population undergoing gastric bypass
surgery [20]. These differences may be due to the differ-
ent populations studied.

The relationship between SCARBI and estrogen may
have biological relevance given that in animals estrogen
regulates the expression of SR-BI and its isoform SR-BII
[21, 22], and that estrogen response elements are found
within the SCARBI promoter [23, 24]. In humans, we
have shown that women undergoing oocyte retrieval for
in vitro fertilization who have low estradiol levels are also
low expressors of SR-BI mRNA [25]. It is possible that
rs5888 or rs3782287 may be in linkage disequilibrium
with a functional variant in estrogen response element in
SCARBI such that carriers of variant alleles for SCARBI
may have altered expression of SR-BI that becomes appar-
ent only in the setting of estrogen. Interestingly, rs5891,
which encodes a missense mutation (Ile135Val), is associ-
ated with HDL-C levels in both age groups. Although
rare, it is possible that the effect of this potentially func-
tional variant is strong enough to be independent of es-
trogen status.

The limitations of our study merit further discussion.
The OOA are a closed founder population with relatively
homogeneous environmental factors and fewer con-
founders of disease and related phenotypes (e.g., low rates
of smoking, alcohol consumption, and medication usage)
[13]. Although this homogenous lifestyle might enhance
our ability to discern genetic influences on disease and
related traits, the ability to generalize our findings will
require further study in the general population. In addi-
tion, the high fat diet of the OOA (approximately 36%
saturated fat (Shuldiner, in preparation)) may also con-
tribute to an interaction between diet, genotype and lipid
levels. Perez-Martinez explored the effect of dietary fat
content (saturated fat diet, carbohydrate-rich diet and a
monounsaturated olive oil diet) on lipid levels in subjects
stratified by the SCARBI exon 1 SNP genotype. Subjects
consuming a saturated fat diet and expressing the minor
allele in exon 1 had significantly higher LDL-C levels
compared to subjects homozygous for the major allele
[26]. This suggests the possibility that dietary fat might
also have an important interaction with other SCARBI
variants. Furthermore, Spady et al. [27] have previously
shown that polyunsaturated fatty acids up-regulate SR-BI
in the hamster.

It should be noted that we reported nominal p values
in our statistical analysis instead of p values adjusted for
multiple comparisons. However, since a major motiva-
tion of our study was to determine if observed associa-
tions between SCARBI SNPs and HDL-C levels were in-
fluenced by age and gender given prior speculations that
genetic effects at this locus might be estrogen sensitive,
the comparisons we considered were not wholly indepen-
dent. Nonetheless, we could not exclude the possibility
of a false-positive association and we need to be cautious
in our interpretation of the results.

In summary, we have shown that some SCARBI vari-
ants are significantly associated with HDL-C levels in partici-
ants of the AFDS. One of these variants encodes a
relatively rare conservative missense mutation and thus
may be functional. Interestingly, there was a significant
age or estrogen interaction with two more common non-
coding SCARBI variants. The clinical relevance of these
associations and the mechanism by which these variants
influence HDL-C levels, especially in younger women,
warrents further study.

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