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Genetic Modulation of Lipid Profiles following Lifestyle Modification or Metformin Treatment: The Diabetes Prevention Program

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Abstract

Weight-loss interventions generally improve lipid profiles and reduce cardiovascular disease risk, but effects are variable and may depend on genetic factors. We performed a genetic association analysis of data from 2,993 participants in the Diabetes Prevention Program to test the hypotheses that a genetic risk score (GRS) based on deleterious alleles at 32 lipid-associated single-nucleotide polymorphisms modifies the effects of lifestyle and/or metformin interventions on lipid levels and nuclear magnetic resonance (NMR) lipoprotein subfraction size and number. Twenty-three loci previously associated with fasting LDL-C, HDL-C, or triglycerides replicated (P = 0.04–1 × 10−17). Except for total HDL particles (r = −0.03, P = 0.26), all components of the lipid profile correlated with the GRS (partial |r| = 0.07–0.17, P = 5 × 10−13–1 × 10−19). The GRS was associated with higher baseline-adjusted 1-year LDL cholesterol levels (β = 0.87, SEE ± 0.22 mg/dl/allele, P = 8 × 10−15, Pinteraction = 0.02) in the lifestyle intervention group, but not in the placebo (β = 0.20, SEE ± 0.22 mg/dl/allele, P = 0.35) or metformin (β = −0.03, SEE ± 0.22 mg/dl/allele, P = 0.90; Pinteraction = 0.64) groups. Similarly, a higher GRS predicted a greater number of baseline-adjusted small LDL particles at 1 year in the lifestyle intervention arm (β = 0.30, SEE ± 0.012 In nmol/L/allele, P = 0.01, Pinteraction = 0.01) but not in the placebo (β = −0.002, SEE ± 0.008 In nmol/L/allele, P = 0.74) or metformin (β = 0.013, SEE ± 0.008 nmol/L/allele, P = 0.12; Pinteraction = 0.24) groups. Our findings suggest that a high genetic burden confers an adverse lipid profile and predicts attenuated response in LDL-C levels and small LDL particle number to dietary and physical activity interventions aimed at weight loss.

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Individual SNP Replication
Thirty-two SNPs previously associated with triglycerides (TG), low-density lipoprotein-cholesterol (LDL-C) and/or high-density lipoprotein-cholesterol (HDL-C) levels were considered [10]. Thirty-one of these were successfully genotyped in the DPP, and two SNPs in CETP, serving as HapMap proxies (r²≥0.90) for rs173539, including rs247616, were subsequently successfully genotyped, with rs247616 retained as the replacement for rs173539. Twenty-three of these 32 non-redundant SNPs replicated with their respective traits in a directionally consistent manner (P<0.05), including 8/11 for TG, 9/14 for HDL-C and 8/11 for LDL-C. Two of the SNPs, rs12678919 and rs964104, replicated for both HDL-C and TG (Table S1).

Association of Individual SNPs with All Four Lipid Traits and Ten Lipoprotein Traits
Additionally, we evaluated the associations of the 32 lipid loci with baseline lipids and nuclear magnetic resonance (NMR)-derived lipoprotein traits [Large HDL particles, Small HDL particles, Total HDL particles, HDL size, LDL size, Total LDL particles, Small LDL particles, Total VLDL particles, Large VLDL particles, VLDL size]. Of all analyses of baseline traits, roughly one third of the tests were nominally significant associations, and 35 associations were significant after correcting for all 448 hypothesis tests; these involved 12 SNPs and 13 traits (Table S2). Interestingly, SNP rs10401969 did not replicate for LDL-C (C vs. T: β±SEM = −0.1±1.6 mg/dl, additive P=0.94), but was associated with decreased large VLDL (mean 5.43, 4.26, 4.07 mmol/L for TT, TC, CC genotypes respectively, additive P=4×10⁻⁶) and smaller VLDL size (53.18, 50.94, 49.55 nm, P=2×10⁻⁶), SNP rs7679 did not quite reach nominal significance for decreased HDL-C (C vs. T: β±SEM = −0.016±0.009 mg/dl, additive P=0.07), but was very strongly associated with increased small HDL particle number (17.93, 20.14 and 21.89 mmol/L for TT, CT and CC genotypes respectively; additive P=4×10⁻³⁶) and consequently total HDL particle number (34.07, 35.10 and 36.78 mmol/L, P=2×10⁻⁶).

Association of Genetic Risk Score (GRS) with Baseline Lipid and Lipoprotein Traits
A lipid GRS was calculated for each individual by first replacing missing genotypes with ethnicity-specific imputed means and then adding up the number of risk alleles possessed for each of the 32 independent SNPs. Of the 32 SNPs evaluated, 11 were originally associated in the meta-analysis with LDL cholesterol, 10 with HDL cholesterol only, seven with triglycerides only, and four with both HDL cholesterol and triglycerides. A risk allele was defined as one associated with increased TG or LDL-C or decreased HDL in the original meta-analysis [10]. After adjustment for age, sex, ethnicity, and BMI, the GRS was significantly associated with all baseline traits evaluated except total HDL particles (P=0.26, Table 2). The following are P-values for the effects of the GRS, as a quantitative covariate, and geometric means for the upper and lower limits of the 95% confidence interval (CI) of the GRS for all four baseline lipids and lipoprotein traits (Table 2).

## Table 1

<table>
<thead>
<tr>
<th>Trait</th>
<th>P-value for GRS</th>
<th>95% CI Lower</th>
<th>95% CI Upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cholesterol</td>
<td>0.02</td>
<td>0.47</td>
<td>0.90</td>
</tr>
<tr>
<td>TG</td>
<td>0.03</td>
<td>0.52</td>
<td>0.99</td>
</tr>
<tr>
<td>HDL</td>
<td>0.04</td>
<td>0.55</td>
<td>0.99</td>
</tr>
<tr>
<td>LDL</td>
<td>0.05</td>
<td>0.56</td>
<td>0.99</td>
</tr>
</tbody>
</table>

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**Introduction**

Dyslipidemia is a strong risk factor for atherosclerotic heart disease [1–3], has a well-defined genetic basis [4], and is modifiable through therapeutic lifestyle changes and weight-loss interventions [5,6]. Individuals at risk for diabetes are also at high risk of cardiovascular disease [7], and individualized lifestyle intervention programs, like the one incorporated into the Diabetes Prevention Program (DPP), have a salutary effect on dyslipidemia and cardiovascular disease risk in this population. However, the cost of widespread implementation of such interventions has been highlighted as a major limitation [8] and not all benefit equally from such interventions. Identifying persons most likely to benefit from intensive lifestyle modification could provide justification for targeting this subpopulation first, making the clinical translation of findings from studies such as the DPP more feasible.

Selection of persons whose dyslipidemia is likely to respond well to lifestyle interventions or pharmacotherapy could help target resources and optimize prevention strategies. To do so requires knowledge of the underlying risk factors for the trait and knowledge of how personal characteristics interact with exercise, diet, and weight loss. Although the heritability of polygenic dyslipidemia [9–11] and its sequelae [12] have been elucidated, little is known of how lifestyle interventions modify the effects of these loci, singly or in combination, on lipid profiles. Thus, learning how a person’s genetic background modulates his or her response to therapeutic lifestyle changes and weight-loss interventions might help optimize the targeting of interventions designed to mitigate cardiovascular and metabolic disease risk.

The purpose of this study was to examine whether loci reliably associated with polygenic dyslipidemia modified the response to cardio-protective interventions in the DPP, a randomized clinical trial of intensive lifestyle modification, metformin treatment, or placebo with standard care. We hypothesized i) that the baseline lipid profiles of DPP participants would be associated with gene variants known to associate with polygenic dyslipidemia and ii) that improvement in lipidemia following treatment would depend on these genetic variants. We also used NMR spectroscopy to characterize the associations of these previously reported loci with lipoprotein subfractions.

## Results

Table 1 shows participant characteristics stratified by DPP treatment arm. The effects of the DPP interventions on 1 yr changes in weight [14], insulin secretion [13], beta-cell function [19], and lipid traits [29] are reported in detail elsewhere.

**Individual SNP Replication**

Thirty-two SNPs previously associated with triglycerides (TG), low-density lipoprotein-cholesterol (LDL-C) and/or high-density lipoprotein-cholesterol (HDL-C) levels were considered [10]. Thirty-one of these were successfully genotyped in the DPP, and two SNPs in CETP, serving as HapMap proxies (r²≥0.90) for rs173539, including rs247616, were subsequently successfully genotyped, with rs247616 retained as the replacement for rs173539. Twenty-three of these 32 non-redundant SNPs replicated with their respective traits in a directionally consistent manner (P<0.05), including 8/11 for TG, 9/14 for HDL-C and 8/11 for LDL-C. Two of the SNPs, rs12678919 and rs964104, replicated for both HDL-C and TG (Table S1).

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Additionally, we evaluated the associations of the 32 lipid loci with baseline lipids and nuclear magnetic resonance (NMR)-derived lipoprotein traits [Large HDL particles, Small HDL particles, Total HDL particles, HDL size, LDL size, Total LDL particles, Small LDL particles, Total VLDL particles, Large VLDL particles, VLDL size]. Of all analyses of baseline traits, roughly one third of the tests were nominally significant associations, and 35 associations were significant after correcting for all 448 hypothesis tests; these involved 12 SNPs and 13 traits (Table S2). Interestingly, SNP rs10401969 did not replicate for LDL-C (C vs. T: β±SEM = −0.1±1.6 mg/dl, additive P=0.94), but was associated with decreased large VLDL (mean 5.43, 4.26, 4.07 mmol/L for TT, TC, CC genotypes respectively, additive P=4×10⁻⁶) and smaller VLDL size (53.18, 50.94, 49.55 nm, P=2×10⁻⁶), SNP rs7679 did not quite reach nominal significance for decreased HDL-C (C vs. T: β±SEM = −0.016±0.009 mg/dl, additive P=0.07), but was very strongly associated with increased small HDL particle number (17.93, 20.14 and 21.89 mmol/L for TT, CT and CC genotypes respectively; additive P=4×10⁻³⁶) and consequently total HDL particle number (34.07, 35.10 and 36.78 mmol/L, P=2×10⁻⁶).

Association of Genetic Risk Score (GRS) with Baseline Lipid and Lipoprotein Traits
A lipid GRS was calculated for each individual by first replacing missing genotypes with ethnicity-specific imputed means and then adding up the number of risk alleles possessed for each of the 32 independent SNPs. Of the 32 SNPs evaluated, 11 were originally associated in the meta-analysis with LDL cholesterol, 10 with HDL cholesterol only, seven with triglycerides only, and four with both HDL cholesterol and triglycerides. A risk allele was defined as one associated with increased TG or LDL-C or decreased HDL in the original meta-analysis [10]. After adjustment for age, sex, ethnicity, and BMI, the GRS was significantly associated with all baseline traits evaluated except total HDL particles (P=0.26, Table 2). The following are P-values for the effects of the GRS, as a quantitative covariate, and geometric means for the upper and lower limits of the 95% confidence interval (CI) of the GRS for all four baseline lipids and lipoprotein traits (Table 2).
Author Summary

The study included 2,993 participants from the Diabetes Prevention Program, a randomized clinical trial of intensive lifestyle intervention, metformin treatment, and placebo control. We examined associations between 32 gene variants that have been reproducibly associated with dyslipidemia and concentrations of lipids and NMR lipoprotein particle sizes and numbers. We also examined whether genetic background influences a person’s response to cardioprotective interventions on lipid levels. Our analysis, which focused on determining whether common genetic variants impact the effects of cardioprotective interventions on lipid and lipoprotein particle size, shows that in persons with a high genetic risk score the benefit of intensive lifestyle intervention on LDL and small LDL particle levels is substantially diminished; this information may be informative for the targeted prevention of elevated lipids and lipoproteins. The NMR subfraction analyses provide novel insight into the biology of dyslipidemia by illustrating how numerous genetic variants that have previously been associated with lipid levels also modulate NMR lipoprotein particle sizes and number. This information may be informative for the targeted prevention of cardiovascular disease.

lower ethnicity-specific GRS quartiles for each trait. A higher GRS was associated with elevated baseline levels of total cholesterol \((P=4\times10^{-11}, 206 \text{ vs. } 195 \text{ mg/dl})\), LDL-C \((P=9\times10^{-2}, 129 \text{ vs. } 121 \text{ mg/dl}; \text{ arithmetic means})\), TG \((P=4\times10^{-10}, 160 \text{ vs. } 127 \text{ mg/dl})\), total VLDL particles \((P=6\times10^{-14}, 67 \text{ vs. } 53 \text{ nmol/L})\), large VLDL particles \((P=1\times10^{-14}, 6.57 \text{ vs. } 4.21 \text{ nmol/L})\), total LDL particles \((P=2\times10^{-10}, 1412 \text{ vs. } 1262 \text{ nmol/L})\), small LDL particles \((P=2\times10^{-11}, 743 \text{ vs. } 543 \text{ nmol/L})\), small HDL particles \((P=0.0005, 19.17 \text{ vs. } 18.10 \text{ µmol/L})\), and VLDL particle size \((P=1\times10^{-5}, 53.86 \text{ vs. } 51.84 \text{ nm})\). A higher GRS was also associated with lower baseline levels of: HDL-C \((P=1\times10^{-15}, 43 \text{ vs. } 47 \text{ mg/dl})\), LDL particle size \((P=1\times10^{-19}, 0.256 \text{ vs. } 0.269 \text{ nm})\), large HDL particles \((P=2\times10^{-8}, 2.98 \text{ vs. } 3.68 \text{ µmol/L})\), and HDL particle size \((P=0.0003, 8.82 \text{ vs. } 8.90 \text{ nm})\). All of these results are consistent with a greater number of risk alleles increasing the atherogenicity of the lipoprotein profile.

GRS \times \text{Intervention Interactions of Baseline-Adjusted One-Year Traits}

Two traits showed evidence of GRS \times \text{lifestyle interaction: } LDL-C \((P=0.02)\) and small LDL particles \((P=0.01, \text{ Table 3; Figure 1; Figure S1a–S1f})\). For these two traits, there was a residual detrimental impact of GRS in the lifestyle (i.e., the GRS was associated with higher levels at one year even after adjusting for baseline levels) but not the metformin or placebo group, suggesting that the lifestyle intervention was less effective at lipid-lowering in those with a higher genetic burden. A unit (allele) GRS increase was associated with higher residual LDL-C levels in the lifestyle group \((\beta=0.087, \text{ SEE }=0.022 \text{ mg/dl}, P=8\times10^{-5})\) but not in the metformin \((\beta=0.03, \text{ SEE }=0.22 \text{ mg/dl}, P=0.90)\) or placebo \((\beta=0.20, \text{ SEE }=0.22 \text{ mg/dl}, P=0.35)\) groups (Figure 1). Similarly, the GRS was associated with higher residual ln-small LDL particles in the lifestyle group \((\beta=0.030, \text{ SEE }=0.0012 \text{ ln nmol/L}, P=0.01)\), but not in the metformin \((\beta=0.013, \text{ SEE }=0.008 \text{ ln nm/}}

<table>
<thead>
<tr>
<th>Trait</th>
<th>Placebo</th>
<th>Metformin</th>
<th>Lifestyle</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>947</td>
<td>939</td>
<td>962</td>
</tr>
<tr>
<td>Age</td>
<td>49 (43–57)</td>
<td>50 (44–57)</td>
<td>49 (42–58)</td>
</tr>
<tr>
<td>Sex (M:F (% male))</td>
<td>290:657 (31% male)</td>
<td>321:618 (34% male)</td>
<td>308:654 (32% male)</td>
</tr>
<tr>
<td>White/AA/Hispanic/Asian/Alt: n (%)</td>
<td>515(54)/207(22)/157(17)/38(4)/30(3)</td>
<td>534(57)/194(21)/155(17)/33(4)/23(3)</td>
<td>517(54)/191(20)/173(18)/53(6)/28(3)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>33.4 (29.2–38.3)</td>
<td>33.0 (29.1–37.7)</td>
<td>32.8 (29.0–37.3)</td>
</tr>
<tr>
<td>Waist Circumference (cm)</td>
<td>104.4 (95–114.7)</td>
<td>104.3 (94.7–114.0)</td>
<td>103.8 (95.0–113.6)</td>
</tr>
<tr>
<td>Total Cholesterol (mg/dL)</td>
<td>201 (178–227)</td>
<td>202 (177–225)</td>
<td>202 (179–227)</td>
</tr>
<tr>
<td>LDL-C (mg/dL)</td>
<td>123 (102–147)</td>
<td>123 (103–145)</td>
<td>124 (102–145)</td>
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<tr>
<td>HDL-C (mg/dL)</td>
<td>43 (37–50)</td>
<td>44 (38–52)</td>
<td>44 (37–53)</td>
</tr>
<tr>
<td>Triglycerides (mg/dL)</td>
<td>146 (102.5–205.5)</td>
<td>135 (97–195)</td>
<td>136 (94–200)</td>
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<tr>
<td>Large HDL particles (µmol/L)</td>
<td>3.3 (2.1–5.5)</td>
<td>3.4 (2.2–5.3)</td>
<td>3.3 (2.2–5.4)</td>
</tr>
<tr>
<td>Small HDL particles (µmol/L)</td>
<td>19 (16.1–22.2)</td>
<td>19.2 (16.3–22.6)</td>
<td>18.9 (15.8–21.8)</td>
</tr>
<tr>
<td>Total HDL particles (µmol/L)</td>
<td>34.1 (30.4–38.5)</td>
<td>34.7 (31.2–38.9)</td>
<td>33.95 (30.2–38.1)</td>
</tr>
<tr>
<td>HDL size (nm)</td>
<td>8.8 (8.6–9.1)</td>
<td>8.8 (8.6–9.1)</td>
<td>8.8 (8.6–9.1)</td>
</tr>
<tr>
<td>LDL size (nm)</td>
<td>0.263 (0.237–0.289)</td>
<td>0.263 (0.237–0.289)</td>
<td>0.263 (0.237–0.289)</td>
</tr>
<tr>
<td>Total LDL particles (µmol/L)</td>
<td>1369 (1140–1629)</td>
<td>1367 (1108–1607)</td>
<td>1332 (1123–1591)</td>
</tr>
<tr>
<td>Small LDL particles (µmol/L)</td>
<td>788 (517–1059)</td>
<td>779 (525–1041)</td>
<td>764 (520–1040)</td>
</tr>
<tr>
<td>Total VLDL particles (µmol/L)</td>
<td>63.3 (43.9–88.1)</td>
<td>62.4 (42.6–86.2)</td>
<td>63.2 (42.1–88.5)</td>
</tr>
<tr>
<td>Large VLDL particles (µmol/L)</td>
<td>5.4 (2.8–10.8)</td>
<td>6.1 (2.8–11)</td>
<td>5.9 (2.7–10.8)</td>
</tr>
<tr>
<td>VLDL size (nm)</td>
<td>52.2 (47.0–58.9)</td>
<td>53.0 (46.9–59.4)</td>
<td>52.8 (47.0–59.0)</td>
</tr>
</tbody>
</table>

doi:10.1371/journal.pgen.1002895.t001
of SNPs included in the GRS are likely to be imperfect proxies for traits shown in Table S3), supporting the conclusion that effects of the interventions. A parsimonious GRS including only those SNPs that are statistically significant in the DPP would likely be overfitted to our data, resulting in biased conclusions about the strength and magnitude of gene × treatment interactions.

Dyslipidemia is a long-established risk factor for CVD [1–3]. Thus, the primary and secondary prevention of atherosclerotic CVD often involves intervening on lipid levels [16]. Lifestyle interventions [17] and metformin treatment [18] that result in weight loss have the potential to improve lipid profiles; nevertheless, as long recognized [19], changes in lipid profiles following interventions vary greatly from one person to the next. Some of the variability in response to interventions may be because genotypes modulate the effects of preventive interventions on lipid homeostasis and CVD risk [20].

Of the many known dyslipidemia-predisposing loci discovered so far [10], only a handful have been the focus of studies testing hypotheses of gene × treatment interactions [21–28], and most of these studies are small (< 150), non-randomized trials of dietary intervention. Although some of these studies have focused on genomic regions that are confirmed to harbor dyslipidemia-predisposing loci, such as APOB, CETP, LIPC and LPL [21,22,24–28], no exhaustive studies testing whether GWAS-discovered loci [10,29,30] modify response to treatments have been previously reported.

The GRS used in this study attenuated the impact of the DPP lifestyle intervention on LDL levels and small LDL particle number. This suggests that a genetic predisposition to high LDL levels and more small LDL particles is difficult to overcome through lifestyle intervention alone. These data also unmask the effects of an underlying genetic defect of LDL levels and small LDL particles found in individuals with a high genetic burden, which becomes visible when adiposity and blood TG content are reduced through lifestyle intervention. This information may justify the combination of lifestyle and lipid lowering drug treatment from the outset in these individuals, rather than the usual approach of stepping from lifestyle to drug therapy when the former fails.

The DPP lifestyle intervention prioritized weight loss, daily fat gram intake and physical activity goals over intake of saturated fat, cholesterol, viscous fiber and plant stanol/sterol; this may have influenced the nature of the changes in the lipid profile. When compared to the metformin and placebo groups, the lifestyle intervention group reported improved physical activity levels and reductions in calorie intake, resulting in significantly greater weight losses [31], each of which has major influences on TG levels. The lifestyle intervention group reported significantly greater reductions in percent calories from total fat and saturated fat than the metformin and placebo groups [31]. However, they did not, on average, achieve the National Cholesterol Education Program target for saturated fat intake and did not focus on the other therapeutic lifestyle changes, such as the additional dietary changes mentioned above, that often have the largest effects on LDL concentrations. The ethnic diversity of the DPP cohort facilitates the generalizability of results, but may also lead to confounding by population stratification in genetic analyses. However, Sensitivity analyses in the European White sub-cohort of the DPP yielded comparable effect estimates to the results obtained in the entire DPP genetics cohort (results for baseline traits shown in Table S3), supporting the conclusion that confounding by population stratification is unlikely to explain our findings.

**Discussion**

In the present study, the majority of previously associated SNPs replicated for baseline lipid traits, and there was a statistically significant relationship between the GRS and the vast majority of standard lipid traits and NMR lipoprotein subfractions. Importantly, in several cases the evidence for association with NMR subfractions was much stronger than for the original standard lipid trait, which may be owing to the relative proximity of the subfractions to the genetic loci. For example, SNP rs7679, originally associated with total HDL-C levels in previous GWASs, in the DPP was not significantly associated with HDL-C \( (P = 0.07) \) but was strongly associated with small HDL particle levels \( (P = 4 \times 10^{-18}) \). This SNP is near PLTP, encoding phospholipid transfer protein, a molecule directly influencing HDL particle size [14]. Such findings extend our understanding of lipid biology and suggest that, compared to standard lipid levels, measurements of lipoprotein subfractions may provide a more effective way of capturing genetically influenced risk. This is particularly important, as recent studies have shown that HDL-C is a heterogeneous trait, which in the context of clinical use may benefit from sub-stratification by genotype [15].

We also observed that within the lifestyle group but not the placebo or metformin groups, the GRS was associated with higher LDL-C and small LDL particle levels after one year of intervention. These findings suggest that the genetic burden on these traits cannot be completely overcome by lifestyle modification. However, even those with the greatest genetic burden benefit to a limited extent from lifestyle intervention in terms of LDL-C reduction (Figure 1A), although the effect on LDL particle size reduction is almost completely ablated (Figure 1B). Even a true residual effect of LDL-C on lifestyle in people with the highest GRS does not negate the clinical relevance of our findings in terms of potential to facilitate tailored treatment decisions. Seeing less of an effect of lifestyle in a particular patient subgroup indicates that these persons may benefit from more frequent surveillance, more intense lifestyle interventions, or aggressive pharmaceutical interventions to supplement lifestyle interventions. Conversely, knowing that lifestyle intervention is likely to be adequate in persons with the lowest genetic burden may maximize the patient’s diet adherence and potentially reduce the costs and side effects associated with prescribing lipid-lowering medications unnecessarily. The availability of information on genetic background may also facilitate patient-provider dialogue, owing to improved diagnostic accuracy. This is similar to the strategy used to control cholesterol levels in patients with a monogenic disorder such as familial hypercholesterolemia due to a severe loss of function mutation in LDLR, where lifestyle intervention combined with pharmacotherapy is needed to bring LDL-C levels within an acceptable range (Third Report of the NCEP-ATP III on the Detection, Evaluation, and Treatment of High Blood Cholesterol in Adults).

It is also important to bear in mind that the interaction effects may be underestimated in our paper. This is because the majority of SNPs included in the GRS are likely to be imperfect proxies for unobserved functional variants, resulting in some degree of genotype misclassification. Moreover, all 32 SNPs were included within the GRS, even though not all SNPs convey statistically significant effects in the DPP and do not individually modify the effects of the interventions. A parsimonious GRS including only those SNPs that are statistically significant in the DPP would likely be overfitted to our data, resulting in biased conclusions about the strength and magnitude of gene × treatment interactions.
Table 2. Association of 32-SNP GRS with Baseline Lipid and Lipoprotein Traits (n=2,843).

<table>
<thead>
<tr>
<th>Trait</th>
<th>Q1 (22–33*)</th>
<th>Q2 (33–35*)</th>
<th>Q3 (35–37*)</th>
<th>Q4 (37–44*)</th>
<th>%diff **</th>
<th>Partial r*</th>
<th>Beta ±SE/unit</th>
<th>p-value ***</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>875</td>
<td>751</td>
<td>636</td>
<td>586</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Chol (mg/dl)</td>
<td>195 (192–197)</td>
<td>199 (196–202)</td>
<td>201 (199–204)</td>
<td>206 (204–209)</td>
<td>6%</td>
<td>0.12</td>
<td>+0.007 ±0.001</td>
<td>4 × 10⁻¹¹</td>
</tr>
<tr>
<td>LDL-C (mg/dl)</td>
<td>121 (119–123)</td>
<td>124 (122–127)</td>
<td>126 (124–129)</td>
<td>129 (127–132)</td>
<td>7%</td>
<td>0.11</td>
<td>+1.01 ±0.19</td>
<td>9 × 10⁻⁸</td>
</tr>
<tr>
<td>HDL-C (mg/dl)</td>
<td>47 (47–48)</td>
<td>46 (45–46)</td>
<td>45 (44–46)</td>
<td>43 (42–44)</td>
<td>9%</td>
<td>–0.15</td>
<td>–0.011 ±0.001</td>
<td>1 × 10⁻¹⁵</td>
</tr>
<tr>
<td>TG (mg/dl)</td>
<td>127 (123–131)</td>
<td>140 (135–145)</td>
<td>146 (141–152)</td>
<td>160 (153–166)</td>
<td>26%</td>
<td>0.14</td>
<td>+0.026 ±0.003</td>
<td>4 × 10⁻¹⁹</td>
</tr>
<tr>
<td>LDL size (nm)</td>
<td>0.269 (0.267–0.271)</td>
<td>0.264 (0.262–0.266)</td>
<td>0.260 (0.258–0.262)</td>
<td>0.256 (0.254–0.258)</td>
<td>5%</td>
<td>–0.17</td>
<td>–0.0059 ±0.0007</td>
<td>1 × 10⁻¹⁹</td>
</tr>
<tr>
<td>Total VLDL particles (nmol/L)</td>
<td>53 (51–55)</td>
<td>59 (56–61)</td>
<td>62 (59–65)</td>
<td>67 (64–71)</td>
<td>26%</td>
<td>0.17</td>
<td>+0.027 ±0.004</td>
<td>6 × 10⁻¹⁴</td>
</tr>
<tr>
<td>Large VLDL particles (nmol/L)</td>
<td>4.21 (3.91–4.54)</td>
<td>4.93 (4.54–5.35)</td>
<td>5.87 (5.37–6.42)</td>
<td>6.57 (5.99–7.2)</td>
<td>56%</td>
<td>0.15</td>
<td>+0.052 ±0.057</td>
<td>1 × 10⁻¹⁴</td>
</tr>
<tr>
<td>Total LDL particles (nmol/L)</td>
<td>1262 (1234–1292)</td>
<td>1304 (1272–1337)</td>
<td>1345 (1308–1382)</td>
<td>1412 (1373–1453)</td>
<td>12%</td>
<td>0.13</td>
<td>+0.013 ±0.002</td>
<td>2 × 10⁻¹⁰</td>
</tr>
<tr>
<td>Small LDL particles (nmol/L)</td>
<td>543 (511–577)</td>
<td>621 (581–664)</td>
<td>703 (654–756)</td>
<td>743 (689–801)</td>
<td>37%</td>
<td>0.17</td>
<td>+0.037 ±0.005</td>
<td>2 × 10⁻¹¹</td>
</tr>
<tr>
<td>Large HDL particles (µmol/L)</td>
<td>3.68 (3.52–3.86)</td>
<td>3.31 (3.15–3.48)</td>
<td>3.21 (3.04–3.39)</td>
<td>2.98 (2.82–3.15)</td>
<td>19%</td>
<td>–0.15</td>
<td>–0.023 ±0.004</td>
<td>2 × 10⁻⁸</td>
</tr>
<tr>
<td>Small HDL particles (µmol/L)</td>
<td>18.10 (17.71–18.49)</td>
<td>18.42 (17.99–18.85)</td>
<td>18.57 (18.1–19.05)</td>
<td>19.17 (18.67–19.69)</td>
<td>6%</td>
<td>0.08</td>
<td>+0.0072 ±0.002</td>
<td>0.0005</td>
</tr>
<tr>
<td>HDL size (nm)</td>
<td>8.90 (8.87–8.93)</td>
<td>8.87 (8.83–8.9)</td>
<td>8.83 (8.8–8.87)</td>
<td>8.82 (8.78–8.85)</td>
<td>1%</td>
<td>–0.07</td>
<td>–0.0011 ±0.0003</td>
<td>0.0003</td>
</tr>
<tr>
<td>VLDL size (nm)</td>
<td>51.84 (51.21–52.48)</td>
<td>52.34 (51.66–53.04)</td>
<td>53.65 (52.88–54.43)</td>
<td>53.86 (53.07–54.66)</td>
<td>4%</td>
<td>0.10</td>
<td>+0.0047 ±0.0011</td>
<td>1 × 10⁻⁵</td>
</tr>
<tr>
<td>Total HDL particles (µmol/L)</td>
<td>34.62 (34.17–35.07)</td>
<td>34.19 (33.71–34.68)</td>
<td>34.52 (33.99–35.06)</td>
<td>34.17 (33.63–34.73)</td>
<td>1%</td>
<td>–0.03</td>
<td>–0.0003 ±0.0012</td>
<td>0.26</td>
</tr>
</tbody>
</table>

*Quartiles were assigned separately in each ethnic group, leading to slight overlap in quartile ranges of number of risk alleles. Traits are age-, sex-, ethnicity- and BMI-adjusted geometric means and 95% confidence intervals, except LDL-C, for which arithmetic mean and 95% confidence interval are shown. Ethnic specific quartile upper limits are 32, 34, 36, 44 alleles for both Whites and African Americans, 32, 35, 37, 43 alleles for Hispanics, 32, 35, 37, 42 alleles for Asians/Pacific Islanders and 33, 34, 36, 40 alleles for American Indians.

**Percent difference between Q4 and Q1 in reference to Q1.

***Partial r and p-value based on analysis of GRS as a quantitative covariate with adjustment for age, sex, ethnicity and BMI.

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Table 3. Association of 32-SNP GRS with Baseline-Adjusted One-Year Lipid and Lipoprotein Traits (n = 2,686).

<table>
<thead>
<tr>
<th>Trait Placebo</th>
<th>Metformin</th>
<th>p</th>
<th>ILS</th>
<th>p</th>
<th>GRS x ILS</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRS^±SE</td>
<td>GRS^±SE</td>
<td>GRSSmet</td>
<td>GRS^±SE</td>
<td>GRS^±SE</td>
<td>GRS^±SE</td>
</tr>
<tr>
<td>n</td>
<td>895</td>
<td>884</td>
<td>–</td>
<td>907</td>
<td>–</td>
</tr>
<tr>
<td>Chol (mg/dl)</td>
<td>+0.001 ± 0.001</td>
<td>–0.0002 ± 0.0012</td>
<td>0.42</td>
<td>+0.004 ± 0.001</td>
<td>0.09</td>
</tr>
<tr>
<td>LDL-C (mg/dl)</td>
<td>+0.20 ± 0.22</td>
<td>–0.03 ± 0.22</td>
<td>0.64</td>
<td>+0.87 ± 0.22</td>
<td>0.02</td>
</tr>
<tr>
<td>HDL-C (mg/dl)</td>
<td>–0.002 ± 0.001</td>
<td>–0.001 ± 0.001</td>
<td>0.78</td>
<td>–0.001 ± 0.002</td>
<td>0.61</td>
</tr>
<tr>
<td>TG (mg/dl)</td>
<td>+0.008 ± 0.004</td>
<td>+0.004 ± 0.004</td>
<td>0.50</td>
<td>+0.005 ± 0.004</td>
<td>0.59</td>
</tr>
<tr>
<td>LDL size (nm)</td>
<td>–0.004 ± 0.009</td>
<td>–0.0022 ± 0.0009</td>
<td>0.17</td>
<td>–0.0024 ± 0.0009</td>
<td>0.22</td>
</tr>
<tr>
<td>Total VLDL particles (nmol/L)</td>
<td>+0.0003 ± 0.0058</td>
<td>+0.0007 ± 0.00054</td>
<td>0.49</td>
<td>+0.0142 ± 0.0009</td>
<td>0.12</td>
</tr>
<tr>
<td>Large VLDL particles (nmol/L)</td>
<td>–0.0036 ± –0.0096</td>
<td>+0.0106 ± 0.0106</td>
<td>0.46</td>
<td>+0.0085 ± 0.0123</td>
<td>0.61</td>
</tr>
<tr>
<td>Total LDL particles (nmol/L)</td>
<td>–0.0028 ± 0.0027</td>
<td>+0.0013 ± 0.0027</td>
<td>0.34</td>
<td>+0.0035 ± 0.0030</td>
<td>0.10</td>
</tr>
<tr>
<td>Large HDL particles (μmol/L)</td>
<td>–0.014 ± 0.006</td>
<td>–0.011 ± 0.006</td>
<td>0.90</td>
<td>–0.009 ± 0.006</td>
<td>0.89</td>
</tr>
<tr>
<td>Small HDL particles (μmol/L)</td>
<td>–0.001 ± 0.003</td>
<td>+0.001 ± 0.003</td>
<td>0.56</td>
<td>+0.001 ± 0.006</td>
<td>0.45</td>
</tr>
<tr>
<td>Small LDL particles (nmol/L)</td>
<td>–0.002 ± 0.008</td>
<td>+0.013 ± 0.008</td>
<td>0.24</td>
<td>+0.030 ± 0.012</td>
<td>0.01</td>
</tr>
<tr>
<td>HDL size (nm)</td>
<td>–0.0004 ± 0.0004</td>
<td>–0.0009 ± 0.0004</td>
<td>0.38</td>
<td>–0.0011 ± 0.0005</td>
<td>0.16</td>
</tr>
<tr>
<td>VLDL size (nm)</td>
<td>–0.00005 ± 0.00165</td>
<td>+0.0005 ± 0.00164</td>
<td>0.97</td>
<td>–0.00096 ± 0.00189</td>
<td>0.54</td>
</tr>
<tr>
<td>Total HDL particles (μmol/L)</td>
<td>–0.0003 ± 0.0015</td>
<td>–0.0021 ± 0.0016</td>
<td>0.36</td>
<td>–0.0010 ± 0.0017</td>
<td>0.76</td>
</tr>
</tbody>
</table>

All traits except LDL-C In-transformed prior to analysis and presentation of beta coefficients and standard errors. Treatment-specific results in bold indicate p<0.05; bold italics indicate p<0.01; underlined bold italics indicate p<0.001.
doi:10.1371/journal.pgen.1002895.t003

Interestingly, no significant interaction was observed between the GRS and other biochemical components of the lipid profile in the present study. It is important to bear in mind, however, that despite being the largest clinical trial of its kind, the DPP is only moderately powered to detect gene*environment interactions [32]; it is likely, therefore, that gene*environment interactions that are small in magnitude will have been overlooked here. Moreover, during the course of writing this paper, many smaller impact lipid loci have been discovered [9,11]. Thus, it is possible that with a larger sample size and the inclusion of some or all of these additional loci, we may have discovered interaction effects on other lipid traits.

In summary, we have shown that common genetic loci that influence polygenic dyslipidemia also modify the effects of clinical interventions designed to mitigate cardiovascular and metabolic risk. This report is the first comprehensive effort to examine validated lipid loci within the context of a large randomized clinical trial. The findings of this study may facilitate the implementation of complex trait genetics into the clinical setting.

## Methods

### Participants

The DPP was a multi-center randomized controlled trial that examined the effects of metformin or intensive lifestyle modification on the incidence of type 2 diabetes [33,34]. Briefly, overweight persons with elevated but non-diabetic fasting and post-challenge glucose levels were randomized to receive placebo, metformin (850 mg twice daily) or a program of intensive lifestyle modification. The lifestyle intervention was designed to achieve ~150 min/wk of physical activity and ~7% weight loss via focus on daily fat gram goals. Fat gram goals were based on initial weight and 25% of calories from fat using a calorie level estimate to produce a weight loss of ~0.5–1 kg/wk. The principal endpoint was the development of diabetes by confirmed semi-annual fasting plasma glucose or annual oral glucose tolerance testing (OGTT). Other phenotypes, such as changes in weight, waist circumference, lipids, insulin and glucose, were also ascertained. Written, informed consent was obtained from each participant, and each of the 27 DPP centers obtained institutional review board approval prior to initiation of the study protocol. A total of 2,993 participants in the placebo, lifestyle and metformin groups had DNA available and provided consent for genetic analysis. Individuals taking lipid lowering medications at baseline (n = 145) were excluded from all analyses.

### Measurements

All participants fasted for ≥12 hrs the night before blood was drawn from an antecubital vein. Standard blood lipid measurements (triglyceride [TG], total cholesterol, HDL-C, calculated LDL-C) were performed at the DPP central biochemistry laboratory. TG and total cholesterol levels were measured using enzymatic methods standardized to the Centers for Disease Control and Prevention reference methods [35]. HDL fractions for cholesterol analysis were obtained by the treatment of whole plasma with dextran sulfate Mg²⁺ [36]. LDL cholesterol was calculated by the Friedwald equation [37]. In participants with TGs>4.5 mmol/L, the lipoprotein fractions were separated using preparative ultracentrifugation of plasma by β quantification [38]. Lipoprotein subclass particle concentrations and average VLDL, LDL, and HDL particle diameters were measured by NMR spectroscopy at LipoScience, Inc (Raleigh, NC) with modification of existing methods [39].

### Genotyping

Thirty-two SNPs previously associated with lipid concentrations in GWAS meta-analyses [10] were selected. DNA was extracted from peripheral blood leukocytes using standard methods. Genotyping was performed by allele-specific primer extension of multiplex amplified products and detection using matrix-assisted laser desorption ionization time-of-flight mass spectrometry on a Sequenom iPLEX platform [40]. The mean genotyping success
incorporate all individuals in the analysis, including those or LDL-C and/or lower HDL-C. In order to be able to design a sar is kal e fit was associated with higher TG using the direction of association from the initial association across ethnicities) prior to score calculation. First, after coding measured (in order to account for allele frequency differences) within each self-reported ethnic group. For the individual SNP analyses, the Bonferroni-corrected \( P \)-value for significance was set at \( P<0.0001 \) to account for multiple comparisons (32 SNPs \( \times 14 \) traits = 448 tests; 0.05/448 = 0.0001).

A genetic risk score (GRS) was calculated from the 32 SNPs using the direction of association from the initial association seen in the published meta-analysis [10]; for each SNP, an allele was designated as a risk allele if it was associated with higher TG or LDL-C and/or lower HDL-C. In order to be able to incorporate all individuals in the analysis, including those missing genotypes at one or more loci, a simple imputation procedure within each self-reported ethnic group was implemented (in order to account for allele frequency differences across ethnicities) prior to score calculation. First, after coding the genotype as the number of minor alleles (0, 1 or 2), an ethnicity-specific mean genotype was calculated and rounded to the nearest whole number. Missing genotypes were replaced by the appropriate rounded mean genotype [41]. We calculated a GRS for each individual by adding up the number of risk alleles for each of the 32 tested SNPs, where a risk allele was defined as one associated with increased TG or LDL-C or decreased HDL.

The GRS was then included as a quantitative independent variable in a multiple regression model for each baseline lipid/lipoprotein trait to test for association, adjusted for age, sex, self-reported ethnicity, and BMI. GRS quartiles were constructed separately within each self-reported ethnicity prior to calculating quartile-specific arithmetic means or geometric means and 95% confidence intervals. To test for interaction of the risk score with treatment, a multiple regression model was constructed with the 1 year value as the outcome variable and including GRS, lifestyle and metformin treatment and GRS \( \times \) lifestyle and GRS \( \times \) metformin terms, along with adjustments for the corresponding baseline trait, baseline age, sex and self-reported ethnicity.

**Sample Size and Power**

A priori power calculations are an important study-planning tool, providing relevant information on likely effect sizes and variances is accessible. It is possible to obtain a broad understanding of the power constraints of our study by extrapolating results from other experimental settings [as described in detail in [42]], but specific a priori power calculations could not be performed for the current study because reliable effect estimates and variances for tests of gene \( \times \) treatment interactions for the index genotypes and phenotypes were unavailable in the published literature at the time this study was planned. Post-hoc power calculations were not performed, as these are well known to cause bias when interpreting a study’s results [43–46]. However, confidence intervals are included in the figures, which give insight into the precision of the GRS effect estimates and hence the power to detect those estimates in the DPP cohort.

**Supporting Information**

**Figure S1** a: Box plots for Small LDL particles measured at baseline in the placebo arm of the Diabetes Prevention Program stratified by level of the genetic risk score. b: Box plots for Small LDL particles measured at baseline in the metformin arm of the Diabetes Prevention Program stratified by level of the genetic risk score. c: Box plots for Small LDL particles measured at baseline in the lifestyle arm of the Diabetes Prevention Program stratified by level of the genetic risk score. d: Box plots for Small LDL particles measured at 1 yr follow-up in the placebo arm of the Diabetes Prevention Program stratified by level of the genetic risk score. e: Box plots for Small LDL particles measured at 1 yr follow-up in the lifestyle arm of the Diabetes Prevention Program stratified by level of the genetic risk score. f: Box plots for Small LDL particles measured at 1 yr follow-up in the lifestyle arm of the Diabetes Prevention Program stratified by level of the genetic risk score.

**Table S1** Details of individual SNP replication results (\( n=2,843 \)). The table compares results for each of the SNP loci in published meta-analysis and elsewhere with those reported here in the DPP. Analyses and means adjusted for age, sex, ethnicity and BMI.

**Table S2** Associations of individual SNPs with lipid or lipoprotein traits significant at the Bonferroni-significant \( P \)-value of <0.0001 for additive model (see Table 1 for units). Shown are geometric means for all traits except LDL-C, for which arithmetic means are shown. All analyses and means adjusted for age, sex, ethnicity and BMI.

**Table S3** Associations of individual SNPs with lipid or lipoprotein traits measured at baseline in White participants from the DPP (\( n=1,565 \)). Analyses were performed to determine whether population stratification owing to the multiethnic nature of the DPP is likely to confound the associations reported in the main analyses. The comparability of the results in White DPP participants with the main analyses indicates that confounding by population stratification is unlikely to underly the main results reported here. Analyses and means adjusted for age, sex, and BMI.
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<thead>
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