**Variation in the Lamin A/C Gene
Associations With Metabolic Syndrome**


**Objective**—Metabolic syndrome is associated with increased risk for cardiovascular disease and type 2 diabetes mellitus (T2DM). The lamin A/C (LMNA) gene, mutations of which cause rare syndromes of severe insulin resistance and dyslipidemia, is located on chromosome 1q21-q24, a region linked to T2DM in several genome wide scans, including in the Old Order Amish. To determine whether polymorphisms in LMNA influence susceptibility to metabolic syndrome and its constituent components.

**Methods and Results**—We performed DNA sequence analysis of LMNA. Six single-nucleotide polymorphisms (SNPs) were identified: c.141889C>T (intron 3), c.141906G>T (intron 3), A287A (c.141253T>C; exon 5), c.140353G>A (intron 6), c.139418C>T (intron 8), and H566H (c. 138747C>T; exon 10). In 971 participants from the Amish Family Diabetes Study, the H566H polymorphism of LMNA was associated with metabolic syndrome diagnosed according to National Cholesterol Education Program ATP III criteria and also higher mean fasting triglyceride and lower mean high-density lipoprotein-cholesterol concentrations. However, no differences in allele frequencies were observed for any SNP among participants with T2DM or impaired glucose homeostasis (IGH) and normoglycemic controls. Haplotype analysis showed that >87% of individuals carried 1 of 2 common LMNA haplotypes. There were no significant differences in haplotype frequencies among subjects with metabolic syndrome T2DM, IGH, and controls.

**Conclusion**—Sequence variation in LMNA may confer modest susceptibility for development of metabolic syndrome and dyslipidemia in the Amish. (Arterioscler Thromb Vasc Biol. 2004;24:1708-1713.)

**Key Words:** lamin A/C ■ lipids ■ triglyceride ■ metabolic syndrome ■ insulin resistance ■ positional cloning ■ chromosome 1q21-q24

Metabolic syndrome is characterized by the presence of ≥3 of the following characteristics: abdominal obesity, elevated triglyceride concentrations, low high-density lipoprotein (HDL), high blood pressure, and elevated fasting glucose. On the basis of estimates from the third National Health and Nutrition Examination Survey, the prevalence of metabolic syndrome is 44% among adults in the United States >50 years of age. Metabolic syndrome is associated with increased risk of type 2 diabetes mellitus (T2DM) and cardiovascular disease. Evidence from the West of Scotland Study indicates that men with metabolic syndrome had 1.7-fold increased risk of a cardiovascular event and 3.5-fold increased risk of developing diabetes. The mechanisms that cause metabolic syndrome are poorly understood but likely involve insulin resistance, which is associated closely with abdominal obesity and is an independent risk factor for cardiovascular disease. Indeed, a large body of evidence supports the notion that adipose tissue factors may mediate several of the metabolic changes that occur with metabolic syndrome. Metabolic syndrome, along with its individual components, is likely to be under the influence of both environmental and genetic factors.

To localize genes contributing to T2DM, cardiovascular disease, and related traits, including obesity and metabolic syndrome, we conducted a genome-wide linkage analysis in large Old Order Amish families from Lancaster County, Pa. Evidence for linkage with T2DM, impaired glucose tolerance, or impaired fasting glucose was observed on chromosome 1q21-q24 (logarithm of odds = 2.35; P<0.0005). This region is a gene-rich region that includes ≥530 genes. Excellent positional candidate genes include APOA (apolipoprotein A2), PPAR γ (per–B-cell leukemia transcription factor 1), slc19a2 (solute carrier family 19 [thiamine transporter] member 2), INSRR (insulin receptor–related receptor gene), KCNJ9 and KCNJ10 (potassium inwardly-rectifying channel, subfamily J, members 9 and 10), PEA 15 (phosphoprotein enriched in astrocytes), RXRG (the γ subunit of the retinoid X receptor).
of the retinoid X receptor),\textsuperscript{12} CRP (C-reactive protein),\textsuperscript{13} HYPLIP1 (familial combined hyperlipidemia gene),\textsuperscript{14} CASQ1 (calsequestrin 1),\textsuperscript{15,16} VAMP 4 (vesicle-associated membrane protein 4);\textsuperscript{17} M Sabra, S Ott, J Lee, JR O’Connell, BD Mitchell, AR Shuldiner, unpublished data, 2004),\textsuperscript{18}\textsuperscript{19} and LMNA (lamin A/C).\textsuperscript{20} This region is approximately 160 to 180 cM from p-telomere and corresponds to a region of chromosome 1 that has been linked to T2DM in several other populations, including Pima Indians,\textsuperscript{21} Utah Mormons,\textsuperscript{22} British whites,\textsuperscript{23} French whites,\textsuperscript{24} and Chinese.\textsuperscript{25}

Familial partial lipodystrophy is a condition associated with severe insulin resistance, diabetes, dyslipidemia, and atherosclerosis,\textsuperscript{26} making LMNA an excellent positional candidate gene for metabolic syndrome, T2DM, and related traits. LMNA, located on chromosome 1q21.2, encodes a nuclear envelope protein that exists as a heterodimer of lamin A and lamin C and is expressed in several cell types including liver, fat, muscle, and pancreas.\textsuperscript{27} The gene contains 12 coding exons. Alternative splicing within exon 10 of LMNA results in coding either the lamin A or lamin C protein. Mutations in LMNA have been shown to result in a number of disorders, including Emery–Dreifuss muscular dystrophy (Online Mendelian Inheritance in Man [OMIM] 181350),\textsuperscript{28}\textsuperscript{29} dilated cardiomyopathy with conduction defects (OMIM 115200),\textsuperscript{30} familial partial lipodystrophy (OMIM 151660),\textsuperscript{31}\textsuperscript{32}\textsuperscript{33}\textsuperscript{34} mandibuloacral dysplasia (MAD; OMIM 248370),\textsuperscript{35} Huchinson–Gilford progeria (OMIM 176670),\textsuperscript{36}\textsuperscript{37}\textsuperscript{38} and autosomal dominant and recessive forms of Charcot Marie tooth disease (OMIM 605588).\textsuperscript{39}–\textsuperscript{40} The mechanism whereby mutations in LMNA lead to these diverse phenotypes is presently unknown.

The aim of this study was to search for novel sequence variation in LMNA and to determine whether variants in this gene influence susceptibility to metabolic syndrome and its constituent components. We sequenced LMNA in 18 Amish subjects diagnosed previously with T2DM from the Amish Family Diabetes Study (AFDS). These individuals were selected from families showing evidence for linkage to the region of interest on chromosome 1. We then performed association and haplotype analyses in the full AFDS cohort to determine whether the polymorphisms identified in LMNA are associated with diabetes, metabolic syndrome, and related traits in the Amish. We found that the polymorphism H565H in exon 10 was associated with metabolic syndrome as well as with higher fasting triglyceride and lower HDL-cholesterol concentrations, suggesting that LMNA variation may confer modest susceptibility for development of metabolic syndrome and dyslipidemia in the Amish.

**Research Design and Methods**

**Subjects**

Subject recruitment for the AFDS began in 1995. Details of the AFDS design, recruitment, phenotyping, and pedigree structures have been described previously.\textsuperscript{2} Briefly, probands were defined as individuals with previously diagnosed diabetes with the age at diagnosis between 35 and 65 years. All first- and second-degree family members \(\geq 18\) years of age were recruited around the diabetic probands. If another diabetic individual was identified in the family (eg, aunt or uncle), the family was expanded further to include the first- and second-degree relatives of that individual \(\geq 18\) years of age. The AFDS participants were divided into 45 families, although all of these families can be joined into a single pedigree by including ancestors going back 12 to 14 generations.\textsuperscript{41}\textsuperscript{42} None of the subjects had known muscular dystrophy, structural or cardiac conduction abnormalities, progeria, or familial partial lipodystrophy, conditions that have been associated previously with mutations in the LMNA gene.

Data regarding medical, social, and family history were obtained during an interview at our Amish Research Clinic or the subject’s home. Height, weight, and waist circumference were measured. Body mass index (BMI) was calculated as weight (kilograms) divided by height squared (\(m^2\)) to estimate total adiposity. Waist circumference was measured by a single observer. For this procedure, subjects were asked to remove any unnecessary clothing. The subject stood erect with the abdomen relaxed, arms at sides, and feet together. The measurer faced the subject and placed an inelastic tape around him/her in a horizontal plane at the level of the natural waist, which is the narrowest part of the torso, as seen from the anterior aspect. In obese subjects, the smallest horizontal circumference was measured in the area between the ribs and iliac crest. The measurement was taken at the end of a normal expiration, without the tape compressing the skin, and recorded to the nearest 0.1 cm. Blood pressure was measured in the left arm with standard sphygmomanometer while the subject was seated after 10 minutes of rest. A single observer made duplicate measurements, and the average of the two readings was used.

Fasting lipid profile (HDL-cholesterol and triglyceride concentrations) was assessed by Quest Diagnostics (Baltimore, Md; interassay coefficient of variation 5.0% for HDL-cholesterol; 1.6% for triglycerides). A 3-hour 75-g oral glucose tolerance test (OGTT) was performed on subjects with no previous history of diabetes. The T2DM diagnosis was defined on the basis of the OGTT using the plasma glucose criteria of the American Diabetes Association (2 hour glucose \(\geq 11.1\) mmol/L or fasting glucose \(\geq 7\) mmol/L). Subjects were also considered to have diabetes if they were currently taking medications for diabetes treatment. Subjects were excluded if there was a history of type 1 diabetes. Additionally, we defined impaired glucose homeostasis (IGH) as 2 hour glucose \(\geq 7.7\) mmol/L and \(< 11.1\) mmol/L or fasting glucose \(\geq 6.1\) mmol/L and \(< 7\) mmol/L. Metabolic syndrome was defined using the National Cholesterol Education Program (NCEP) ATP III guidelines.\textsuperscript{43} It is characterized by the presence of \(\geq 3\) of the following characteristics: abdominal obesity (waist circumference \(>120\) cm for men and \(>88\) cm for women), elevated triglycerides (>1.68 mmol/L), low HDL (<1.03 mmol/L for men and <1.29 mmol/L for women), high blood pressure (\(\geq 130/85\) mm Hg), and elevated fasting glucose (>6.0 mmol/L). Clinical characteristics of Amish subjects are shown in Table 1.

The mean age of diagnosis of diabetes in the AFDS cohort was 59.7 ± 11.0 years (range 35 to 83 years), and the mean BMI was 28.8 ± 5.2 kg/m\(^2\) (range 16.4 to 40.7 kg/m\(^2\)). The 18 AFDS subjects selected for screening for mutations in LMNA in this study were individuals with diabetes who were members of different nuclear families that showed evidence for linkage to the area of interest on chromosome 1. The mean age of these 18 subjects was 61.3 ± 12.3 years (range 49 to 90 years). The study was conducted in accordance with the human subject standards of the institutional review board of the University of Maryland, and informed consent was obtained from all subjects.

**Laboratory Methods**

Whole blood was collected from the subjects, and genomic DNA was isolated using Maxipreps according to the instructions of the manufacturer (Qiagen). All 12 exons as well as the exon–intron junctions of LMNA were amplified by polymerase chain reaction (PCR). Primers for DNA amplification and sequencing were derived using the published sequence for LMNA (GenBank AC007227; Table I, available online at http://atvb.ahajournals.org). DNA sequencing was performed using an Applied Biosystems 377 automated DNA sequencer (Perkin–Elmer). PCR products were sequenced in both directions, visually inspected, and compared with the GenBank sequence of human LMNA.

Genotyping was completed using an Orchid SNPstream UHT genotyping system (Orchid Bioscience). First, the target genomic sequences containing the single-nucleotide polymorphisms (SNPs) of interest were amplified in a 12-plex PCR reaction. After enzymatic clean-up, PCR products were subjected to an extension
reaction using 5′-tagged extension primers and fluorescent dye-labeled terminators. In a thermal cycled extension step, the primers hybridized to the specific amplicons 1 base adjacent to the SNP site and were extended by 1 base at the 3′ end with a fluorescently labeled nucleotide. These reaction products were transferred to an array plate, where each of the 12 extension products in the multiplex reaction was sorted by hybridization of the unique 5′-tag sequence to its complementary probe immobilized in a miniarray within each well. The Orchid SNPscope reader imaged the microarray plates. The 2-color detection allowed SNP detection by comparing signals from the 2 fluorescent dyes. The image signals were then transferred to genotyping software that translated the images of the arrays into specific means, to that of a nested model in which genotypic means were compared the likelihood of a full model, which allowed for genotypic-specific genetic models given the pedigree structure. For example, we compared the likelihood of linkage disequilibrium between the 2 intron 3 SNPs (r² = 0.93; D′ = 1), moderate between the intron 3 SNPs and SNPs at exon 5, intron 6, and intron 8, and among the latter SNPs (r² = 0.45 to 0.84; D′ = 0.94 to 1) and weaker between the exon 10 SNP and all others (r² = 0.02 to 0.12; D′ = 0.35 to 1; see Table 3).

The prevalence rates for T2DM and IGH were 9.8% and 25.9%, respectively, in this sample. Allele and genotype frequencies did not differ between T2DM cases and controls for any of the 6 SNPs, nor was there evidence for association of any of the SNPs with the composite trait T2DM/IGH (Table 2). We examined the relationships between BMI and metabolic syndrome–related traits and LMNA sequence variants. Mean levels of obesity and lipid measures are also shown in Table 2 according to the exon 10 H566H (c.138747C>T) genotype. Triglyceride concentrations were higher and HDL concentrations lower in subjects with the T allele (P = 0.004 and 0.03, respectively). There was also a significant association with metabolic syndrome as defined by NCEP ATP III guidelines (P = 0.017, odds ratio 1.43; CI 1.05 to 1.80).

Corresponding analyses of the exon 5 A287A (c.141253T>C) SNP showed higher fasting glucose among those with the C allele than those with the TT genotype (P = 0.001). No significant association with obesity measures, lipid traits, or blood pressure was seen for this SNP. Analysis of the intronic SNPs showed no significant association with obesity, lipid traits, or metabolic syndrome (data not shown).

As a secondary analysis of the exon 10 variant H566H (c.138747C>T), we evaluated whether the effects of the exon...
10 CT/TT genotype on metabolic syndrome and related traits differed between men and women or between younger or older individuals. There was little evidence that the genotype effect differed between men and women for any trait. For triglycerides, age-stratified analyses indicated that the genotype effect differed little between younger and older men, although the effect of the CT/TT genotype was restricted almost entirely to those younger than age 50, respectively. However, in women, the effect of the CT/TT genotype was restricted almost entirely to those older than age 50 years. This interaction effect did not achieve statistical significance ($P=0.17$).

We next considered the possibility that haplotypes defined by allelic combinations at these 6 SNPs might show associations with either disease status or with quantitative trait levels. Because of marked linkage disequilibrium between markers (Table 3), 2 most frequent haplotypes (C138747-T141253-T138747-T141906 and T138747-T141253-C139418-G140353-C141889-T141906) together accounted for $>87\%$ of the haplotypes in the Amish. The estimated frequencies of the first 2 most common haplotypes are 0.548292 and 0.327621, respectively. There were no significant differences in haplotype frequencies among subjects with T2DM or metabolic syndrome and controls, nor were there any differences in glucose, insulin, obesity, or lipid traits between haplotypes.

### Discussion

Mutations in LMNA have been found in diseases involving muscle and fat cells and include Emery–Dreifuss muscular dystrophy,28,29 dilated cardiomyopathy with conduction defects,30 familial partial lipodystrophy,31–34 MAD,35 and Charcot Marie tooth disease,36–38 as well as premature aging.36–38 Familial partial lipodystrophy is associated with severe insulin resistance, diabetes, dyslipidemia, and atherosclerosis.26 Our genome-wide scan in the Amish and those of several others21–25 provide strong evidence for the existence of $\geq1$ T2DM susceptibility genes on chromosome 1q21-q24, the region in which LMNA resides. These observations led us to sequence all of the exons and exon--intron boundaries of LMNA in subjects with diabetes from Amish families, providing evidence for linkage to chromosome 1q21-q24. Although our mutation screen detected 6 SNPs, none resulted in obvious alterations in protein structure, and none were associated with T2DM or IGH. We did not screen for mutations in regulatory regions or the entirety of all introns, and thus cannot rule out the possibility that significant mutations may be present in these regions. However, lack of association of any haplotype with T2DM or related traits make this possibility less likely. Thus, LMNA is unlikely to be the gene on chromosome 1q21-q24 detected through linkage analysis contributing to risk of T2DM.

Modest associations with a common variant in exon 10 of LMNA (H566H) have been shown to be associated with adipose tissue metabolism and obesity phenotypes.48–50 In Canadian Oji-Cree and Inuit, this variant was associated with
BMI, waist-to-hip ratio, leptin, and body fat percentage.\textsuperscript{48,49} Additionally, this variant has been studied in a Japanese cohort\textsuperscript{44} and in Pima Indians.\textsuperscript{50,51} In Pimas, no evidence for association of H566H with T2DM, BMI, total cholesterol, HDL-cholesterol triglycerides, or indices of insulin sensitivity and secretion was found.\textsuperscript{51} However, Pimas with the T allele had significantly greater subcutaneous fat cell size.\textsuperscript{50} In the Japanese cohort, this variant was associated with higher fasting insulin, triglyceride, total cholesterol concentrations, and lower HDL-cholesterol concentrations.\textsuperscript{44}

Amish individuals who were exposed to the T allele of the c.138747C>T variant had higher triglyceride concentrations and lower HDL-cholesterol and were more likely to have the presence of metabolic syndrome. Thus, it is possible that this variant plays a modest role in modulating the metabolic syndrome, particularly lipid components.

Although this SNP encodes a silent mutation H566H, it is the terminal exon nucleotide of exon 10, the site of alternate splicing for lamin A and C mRNA. This polymorphism could alter mRNA splicing and thus the relative amounts of lamin A and C mRNA and protein. Indeed, the silent \textit{LMNA} G608G SNP has been shown to cause aberrant mRNA splicing and to cause Hutchinson–Gilford progeria.\textsuperscript{36}

In summary, screening of \textit{LMNA} revealed 6 SNPs. One SNP, H566H (c.138747C>T), showed significant association with metabolic syndrome and with lower HDL-cholesterol and higher triglyceride concentrations. These associations are consistent with other studies reporting association of this same variant with metabolic syndrome traits. None of the SNPs or haplotypes examined showed evidence of association with T2DM or IGH. We conclude that genetic variation in \textit{LMNA} may play a modest role in susceptibility to metabolic syndrome and dyslipidemia in our population but is unlikely to be the gene on chromosome 1q21-q24 detected through linkage analysis contributing to risk of T2DM.

\textbf{Acknowledgments}
This work was supported by a scientist development grant of the American Heart Association (N.I.S.), National Institutes of Health grants K24 DK02673 and R01 DK 54261, an American Diabetes Association research award (A.R.S.), and the University of Maryland General Clinical Research Center. A.R.S. is also supported by the Baltimore Veterans Administration Geriatric Research and Education Clinical Center. We thank Drs Richa Agarwala and Alejandro Schäffer for their assistance in pedigree construction using the Anabaptist Genealogy Database. We also wish to acknowledge Demian Lewis, Sandy Ott, and Dr Arnel Tagle for technical assistance, and Dr Holmes Morton and Caroline Morton for their support in establishing and maintaining ties with the Amish community. Finally, we gratefully acknowledge our Amish liaisons and field workers and the extraordinary cooperation and support of the Amish community without which these studies would not have been possible.

\textbf{References}
15. Howarth FC, Glover L, Culligan K, Qureshi MA, Ohlendiek K. Calsequestrin expression and calcium binding is increased in streptozotocin-

\textbf{TABLE 3. Pairwise Linkage Disequilibrium Coefficients ($D’$ and $r^2$) for LMNA SNPs in the Old Order Amish}\n
<table>
<thead>
<tr>
<th>SNP</th>
<th>Intron 3 141889C&gt;T (0.05)</th>
<th>Intron 3 141906G&gt;T (0.09)</th>
<th>Exon 5 A287A 141253T&gt;C (0.08)</th>
<th>Intron 6 140353G&gt;A (0.09)</th>
<th>Intron 8 139418C&gt;T (0.11)</th>
<th>Exon 10 H566H 138747C&gt;T (0.35)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intron 3</td>
<td>1.00</td>
<td>0.93</td>
<td>0.64</td>
<td>0.63</td>
<td>0.49</td>
<td>0.02</td>
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<tr>
<td>Intron 3</td>
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<td>0.45</td>
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<td>0.12</td>
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<tr>
<td>Exon 5</td>
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<td>1.00</td>
<td>0.95</td>
<td>0.77</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Intron 6</td>
<td>1.00</td>
<td>1.00</td>
<td>0.94</td>
<td>1.00</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Intron 8</td>
<td>1.00</td>
<td>1.00</td>
<td>0.48</td>
<td>0.35</td>
<td>0.41</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Allele frequency is in parentheses. Upper triangle, $r^2$; lower triangle, $D’$. \textcopyright 1990 Elsevier Science Inc.


29. Agarwala R, Biesecker LG, Hopkins KA, Fanromano CM, Schaffer AA. Software for constructing and verifying pedigrees within large genealogies and an application to the Old Order Amish of Lancaster County, Genome Res. 1998;8:211–221.


39. Agarwala R, Biesecker LG, Hopkins KA, Fanromano CM, Schaffer AA. Software for constructing and verifying pedigrees within large genealogies and an application to the Old Order Amish of Lancaster County, Genome Res. 1998;8:211–221.


46. Hegele RA, Huff MW, Young TK. Common genomic variation in LMNA Gene and Metabolic Syndrome 1713


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Arterioscler Thromb Vasc Biol. 2004;24:1708-1713; originally published online June 17, 2004; doi: 10.1161/01.ATV.0000136384.53705.c9
Arteriosclerosis, Thrombosis, and Vascular Biology is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 1079-5642. Online ISSN: 1524-4636

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