Integrated Computational and Experimental Analysis of the Neuroendocrine Transcriptome in Genetic Hypertension Identifies Novel Control Points for the Cardiometabolic Syndrome

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Background—Essential hypertension, a common complex disease, displays substantial genetic influence. Contemporary methods to dissect the genetic basis of complex diseases such as the genomewide association study are powerful, yet a large gap exists between the fraction of population trait variance explained by such associations and total disease heritability.

Methods and Results—We developed a novel, integrative method (combining animal models, transcriptomics, bioinformatics, molecular biology, and trait-extreme phenotypes) to identify candidate genes for essential hypertension and the metabolic syndrome. We first undertook transcriptome profiling on adrenal glands from blood pressure extreme mouse strains: the hypertensive BPH (blood pressure high) and hypotensive BPL (blood pressure low). Microarray data clustering revealed a striking pattern of global underexpression of intermediary metabolism transcripts in BPH. The MITRA algorithm identified a conserved motif in the transcriptional regulatory regions of the underexpressed metabolic genes, and we then hypothesized that regulation through this motif contributed to the global underexpression. Luciferase reporter assays demonstrated transcriptional activity of the motif through transcription factors HOXA3, SRY, and YY1. We finally hypothesized that genetic variation at HOXA3, SRY, and YY1 might predict blood pressure and other metabolic syndrome traits in humans. Tagging variants for each locus were associated with blood pressure in a human population blood pressure extreme sample with the most extensive associations for YY1 tagging single nucleotide polymorphisms rs11625658 on systolic blood pressure, diastolic blood pressure, body mass index, and fasting glucose. Meta-analysis extended the YY1 results into 2 additional large population samples with significant effects preserved on diastolic blood pressure, body mass index, and fasting glucose.

Conclusions—The results outline an innovative, systematic approach to the genetic pathogenesis of complex cardiovascular disease traits and point to transcription factor YY1 as a potential candidate gene involved in essential hypertension and the cardiometabolic syndrome.

Key Words: BPH mouse strain complex trait essential (genetic) hypertension human genetics metabolic syndrome

Essential hypertension, a common disease, displays substantial genetic influence with heritability estimates for blood pressure up to approximately 50%.1 The complex, multifactorial nature of this disorder, however, has made it difficult to identify underlying genetic contributors. Investigation of such complex traits with novel and integrative methods might be required to completely understand their genetic basis.

Clinical Perspective on p 440

In the current report, we present a novel method that begins with genomewide transcriptome profiling and then

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sequentially integrates several disciplines and tools (animal models, microarray technology, bioinformatics, molecular biology, extreme phenotypes, and human genetics) to create, filter, and refine a list of candidate genes for essential hypertension and the metabolic syndrome (a cluster of risk factors for cardiovascular disease, including essential hypertension, insulin resistance, dyslipidemia, and elevated plasma cholesterol).

Our analysis is based on 2 inbred, blood pressure extreme mouse strains, the hypertensive BPH (blood pressure high) and the hypotensive BPL (blood pressure low). The use of extreme phenotypes has been suggested for the study of complex traits as a strategy to increase the power of detecting underlying genetic determinants as well as rare variants. The BPH strain parallels human essential hypertension, with elevated blood pressure, increased heart rate, and early mortality. Although BPH was developed through selection solely on blood pressure, the strain exhibits several metabolic syndrome-like abnormalities such as decreased plasma high-density lipoprotein (HDL) cholesterol, enhanced rate of body weight gain on a high-fat diet, and increased pulse rate.

We chose the adrenal gland as the target of microarray analysis of BPH and BPL because its secretory products, both mediullary and cortical, determine endocrine, cardiovascular, and sympathetic functions important in hypertension and the metabolic syndrome. For example, mediullary catecholamines act through G-protein-coupled adrenergic receptors to modulate force of contraction of the heart and constriction of blood vessels and regulate carbohydrate and lipid metabolism through effects on glucagon and insulin secretion, glycogenolysis, glycolysis, and lipolysis. Cortical steroid hormones regulate reabsorption and secretion of sodium and potassium (mineralocorticoids) and modulate carbohydrate and lipid metabolism (eg, through effects on peripheral glucose uptake, gluconeogenesis, and lipolysis) as well as inflammation (glucocorticoids).

After microarray analysis, bioinformatic, molecular biology, and human genetic tools were applied sequentially to identify significant association (by meta-analysis) of YYI rs11625658 single nucleotide polymorphism (SNP) genotype with diastolic blood pressure (DBP), body mass index (BMI), and glucose across 3 large human cohorts, suggesting shared genetic determination for such metabolic syndrome traits. Uniquely, we focused on transcription factors as candidate gene “master switches” because functional changes in them are likely to be pleiotropic and, therefore, provide a unifying genetic mechanism for multiple traits of the metabolic syndrome.

Methods

Mouse Strains

Juvenile (approximately 5-week-old) and adult (approximately 12-week-old), hypertensive (strain=BPH) and hypotensive (strain=BPL) inbred male mice were obtained from colonies at the Jackson Laboratory (Bar Harbor, ME). Systolic blood pressure of the BPH strain parallels human essential hypertension, with elevated blood pressure, increased heart rate, and early mortality. Although BPH was developed through selection solely on blood pressure, the strain exhibits several metabolic syndrome-like abnormalities such as decreased plasma high-density lipoprotein (HDL) cholesterol, enhanced rate of body weight gain on a high-fat diet, and increased pulse rate.

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Construction of Promoter or Enhancer/Luciferase Reporter Plasmids

Cloning of the motif oligonucleotide sequences was accomplished at the unique Xhol (promoter) or SalI (enhancer) restriction enzyme sites in pGL3-Promoter. The 2 oligos (S'-[phosphosphate] TCGAGACC ATAGATAC-3'; 5'-[phosphate] TCGGATATCATCTAGTGC-3') were annealed in the following reaction mixture: 162.5 pmol each of oligo plus water for a total of 75 μL and 25 μL of annealing buffer (100 mM Tris pH 7.5, 100 mMol/L MgCl2, 10 mMol/L DTT). The annealing reaction mixture was heated at 90°C for 5 minutes and then allowed to cool to room temperature over a period of 45 minutes. To test the transcriptional effects of the motif when it is located in the proximal promoter region of a gene, the annealed oligos were inserted into the unique Xhol site just upstream of the SV40 promoter in the multiple cloning site of the firefly luciferase reporter vector, pGL3-Promoter (Promega). To allow for testing of transcriptional “enhancer” (distant) effects of the motif, the annealed oligos were inserted in the SalI restriction enzyme site just downstream of the luciferase gene poly-A signal in the pGL3-Promoter vector (Promega). The oligos inserted in the “enhancer” position were designed with the following sequence: S'-[phosphate] CTAGACC ATAGATAC-3'; 5'-[phosphate] TCGGATATCATCTAGTGC-3'. A total of 4 types of luciferase reporter plasmids was constructed with the motif being inserted in either the “promoter” or “enhancer” position in either the forward or reverse orientation. Insertion of the motif in 2 directions enabled testing of orientation specific effects.

Adrenal Cell Promoter/Reporter Transfection and Luciferase Activity Assays

Rat PC12 pheochromocytoma cells (grown in Dulbecco’s modified Eagle’s medium high glucose [Invitrogen] with 5% heat-inactivated fetal bovine serum [Gemini Bioproducts, Woodland, CA], 10% heat-inactivated horse serum [Gemini Bioproducts, Woodland, CA], penicillin [100 U/mL], streptomycin [100 μg/mL], and 1-glutamine [0.292 mg/mL]) were transfected (at 50%–60% confluence, 1 day after splitting 1:4) with motif-promoter (XhoI; forward or reverse orientation) or motif enhancer (SalI; forward or reverse orientation) reporter vector DNA (1 μg supercoiled DNA per well; 12-well polystyrene plates [coated with poly-l-lysine; Sigma], 2.2-cm diameter wells, Corning Inc, Corning, NY) using the liposome method (Superfect; Qiagen). Cotransfection of mammalian expression (CMV-promoter) transcription factor plasmids was performed with 50 ng of pcDNA3.1(-) (empty vector control; Invitrogen, Carlsbad, CA), HoxA3 (Mus musculus; MMM1013–98478526; Open Biosystems, Huntsville, AL), MEF2A (Homo sapiens; SC118004, OriGene, Rockville, MD). Cells were lysed 20 hours after transfection with lysis buffer (300 μL per well; 0.1 mol/L phosphate buffer [K-HPO4+KH2PO4; pH 7.8], 1 mmol/L DTT, and 0.1% Triton-X 100). The bioluminescent activity of luciferase in 80 μL of cell lysate was determined with the AutoLumat LB 953 luminometer (EG&G Berthold, Nashua, NH) by measuring light emission (incubation time=0 seconds, measure time=10 seconds, temperature=25°C) after addition of assay buffer (100 μL per sample; 100 mmol/L Tris-acetate [pH 7.8], 10 mmol/L Mg-acetate, 1 mmol/L EDTA [pH 8.0], 3 mmol/L adenosine 5'-triphosphate, and 100 μmol/L luciferin [Sigma-Aldrich]). As a control for varying cell number between individual wells, the total protein content was measured in the cell lysate using the Bio-Rad Protein Assay (Coomassie blue dye absorbance shift; based on the Bradford method; Bio-Rad, Hercules, CA). Luciferase activity (n=4–5 wells/condition) is expressed as the normalized ratio of (luciferase activity)/total protein) or (RLU/μg protein). Data were analyzed with analysis of variance followed by pairwise t tests corrected for multiple comparisons (Bonferroni).

Human Subjects

Population Blood Pressure Extremes

We previously published a detailed description of the human subjects and subject selection criteria used in this investigation.20 Unrelated adults from the Kaiser-Permanente Medical Group (subscription-based Health Maintenance Organization) primary care population located in San Diego, CA, were selected from the lowest and highest (extreme) percentiles of diastolic blood pressure (DBP) distribution (≤63 mm Hg or ≥90 mm Hg); subjects were ascertained on the DBP trait, because twin and family studies provide evidence that DBP is substantially heritable.1–24 and SBP correlates highly with DBP. Two independent DBP extreme samples (cohort 1: n=996; cohort 2: n=1075) were obtained from different individuals within the source population. Blood pressure was measured in seated subjects using brachial sphygmomanometry. If DBP was elevated, repeat measurement was obtained for verification (only the initial value was reported; values were not averaged). Approximately 48% of the hypertensive subjects from the upper DBP extreme reported being prescribed and taking one or more antihypertensive medication. Subjects in the lower extreme DBP group reported no history of hypertension or antihypertensive medication. Subjects did not have renal failure (serum creatinine concentration was ≤1.5 mg/dL in 98.6% of subjects). Self-identified ethnicity (including that of both parents and all 4 grandparents) for all subjects was specified as white (European ancestry). Medical information was obtained from annual health appraisal visits and questionnaire. Blood for preparation of genomic DNA was obtained with informed consent, and samples were deidentified.

Extension of Human Genetic Association: ICBP-GWAS (International Consortium of Blood Pressure–Genome Wide Association Studies)

Extension of associations in our two blood pressure extreme cohorts was sought in the International Consortium of Blood Pressure (ICBP GWAS).25 Complete details of ICBP methodology have previously been presented.26 In short, ICBP data (www.igm.jhmi.edu/gehret/icbp-p32413ahsfd134/icbp_08802401234–9812599.html) were analyzed in separate genomewide meta-analyses for SBP and DBP. Before meta-analysis, the association results for each cohort were filtered to exclude SNPs not in HapMap. SNPs with alleles different from HapMap, and SNPs with observed/expected ratio of coded genotype scores <0.3. A genomic control correction was applied. Where studies stratified their analyses by sex, genomic control was applied within each sex stratum. For each SNP, the per-coded-allele effects were combined across studies (and across sex strata, when used) using inverse variance-weighted meta-analysis.

Genotyping and Statistical Analysis

The HMap (http://hapmap.ncbi.nlm.nih.gov) was used to select common (minor allele frequency >5%), validated tagging SNPs that capture the linkage disequilibrium and haplotype block structure within candidate genes using CEU (European ancestry) subject data. By inspection of CEU linkage disequilibrium heat plots, each target locus (HOXA3, 7.8 kb; YY1, 39.7 kb; and SRY at 896 bp) was spanned by a single linkage disequilibrium block in CEU subjects. A total of 7 SNPs were selected to tag these 3 loci (at 2–3 SNPs per locus): 2 at HOXA3 (rs10085570, rs6948297), 1 at SRY (rs2058276), and 1 at YY1 (rs8021803, rs11625658, rs4905941). The HOXA3 and YY1 tagging SNPs were located within introns. SRY tagging SNPs were located adjacent to the SRY gene in the 5'-upstream region. SNP genotyping was performed on subjects’ genomic DNA with the matrix-assisted laser desorption ionization
time-of-flight mass spectrometry system developed by Sequenom, as previously described.20

Statistical association between individual SNPs and individual metabolic syndrome traits was tested with univariate analysis of variance (independent variable=diploid genotype [additive model]; dependent variable=one metabolic syndrome trait; covariates=age, sex). A false discovery rate (<0.05) was used to control for testing of multiple genotypes and phenotypes, as described21 and applied20,25 in the literature. A total of 6 phenotypes were tested for association: SBP, DBP, body mass index (BMI), (fasting) plasma glucose, total cholesterol, and HDL cholesterol. Plasma triglyceride and low-density lipoprotein cholesterol data were not available in these subjects. A second control for testing of multiple phenotypes was also achieved using multivariate analysis of variance, wherein statistical association between individual SNPs and multiple metabolic syndrome traits was evaluated simultaneously using one test (multivariate analysis of variance: independent variable=diploid genotype [additive model]; dependent variable=SBP, DBP, BMI, plasma glucose, plasma cholesterol, and/or plasma HDL cholesterol; covariates=age, sex). We included age and sex as covariates to control for their effects on blood pressure and metabolic phenotypes. No adjustment was made for the use of antihypertensive medication. Blood pressure data can be adjusted for antihypertensive therapy (with, for example, the method described by Cui30); however, without adjustment, our analysis was likely more conservative, that is, biased toward the null (insignificance), because adjustment would tend to disproportionately increase the mean blood pressure of diploid genotype groups consisting of a higher proportion of hypertensive subjects. The effect size for significant SNPs is presented as partial η-squared (η2); the proportion of total trait variance attributable to a specific SNP. Statistical analyses were performed using SPSS software (SPSS Inc, Chicago, IL). Data are presented as means±SEM.

To evaluate the cumulative effect of genetic variation at YY1 on metabolic syndrome traits in the 3 groups (San Diego cohorts 1 and 2; ICBP-GWAS), we turned to meta-analysis using the outcomes of regression analysis (additive model) in each group, focusing on the effect size β (slope per allele) and the SE of β using the command METAN within the program STATA (Stata Corporation, College Station, TX; www.stata.com) reporting results of fixed effect (ie, genotype as independent variable) models.

Results

Microarray Adrenal mRNA Expression Analysis

Previous statistical analysis of the BPH and BPL adrenal microarray data identified 2004 significantly differentially expressed genes—approximately 16% of all probe sets9,10 (online-only Data Supplement Table I). The distribution of differential expression was split approximately evenly between overexpression (924 of 2004 genes [46%]) and underexpression (1080 of 2004 genes [54%]) in BPH versus BPL.

We used GenMAPP to functionally cluster the microarray data into statistically significant biochemical systems and pathways. GenMAPP identified 7 biochemical pathways within the intermediary metabolism domain (the set of canonical biochemical pathways responsible for intracellular energy production, ie, adenosine 5′-triphosphate formation resulting from carbohydrate or lipid metabolism) of the BPH that were significantly perturbed: the electron transport chain (P<0.001), fatty acid degradation (P<0.01), fatty acid synthesis (P<0.001), glycolysis/glucoseogenesis (P<0.001), mitochondrial long chain fatty acid β-oxidation (P<0.001), pentose phosphate (P<0.004), and tricarboxylic acid cycle (P<0.001) pathways (online-only Data Supplement Table II). In addition, all of the significantly perturbed intermediary metabolism pathways were also globally underexpressed in BPH: the electron transport chain (P<0.0001), fatty acid degradation (P=0.011), fatty acid synthesis (P=0.031), glycolysis/glucoseogenesis (P=0.006), mitochondrial long chain fatty acid β-oxidation (P=0.021), pentose phosphate (P=0.031), and tricarboxylic acid cycle pathways (P=0.0005; Fisher exact test; online-only Data Supplement Table II). The tricarboxylic acid cycle pathway exhibited a pattern of global underexpression representative of that observed in all of the intermediary metabolism pathways (online-only Data Supplement Figure I). In total, 82 genes of the intermediary metabolism pathways were differentially expressed with the directional pattern of expression significantly and globally shifted toward underexpression: 79 of 82 genes were underexpressed, whereas 3 of 82 genes were overexpressed (P<0.0001; Fisher exact test).

Computational Promoter Motif Identification

The MITRA algorithm was used to identify statistically overrepresented transcription factor binding motifs in regulatory sequences from the set of 82 differentially expressed genes (79 underexpressed, 3 overexpressed) in intermediary metabolism of the BPH adrenal gland. MITRA identified one significantly overrepresented (P<0.05) 10-bp motif that was present a total of 55 times in 38 of the 82 (38 of 82 [46%]) differentially expressed metabolic genes: 5′-ACCATAGTN-3′ (Figure 1; online-only Data Supplement Table III). The motif was not localized to a limited set of subpathways of intermediary metabolism (eg, only in the tricarboxylic acid cycle and pentose phosphate subpathways) but instead was present in an approximately equal proportion of differentially expressed
genes (approximately 50%; \( P=0.97, \chi^2 \) test) in each of the sub-pathways of intermediary metabolism.

**Promoter/Luciferase Reporter Assays: Determination of Motif Transcriptional Activity**

Promoter/luciferase reporter plasmid constructs were used to determine if the motif conferred transcriptional activity. Because positions 8 and 10 in the motif consensus sequence (5'-ACCATAGNTN-3') lacked nucleotide preference ("N"), adenine ("A") was randomly and independently chosen to fill each "N" position in the motif (5'-ACCATAGATA-3'). The motif was inserted in 2 regions of the pGL3-promoter luciferase reporter plasmid (driven by the SV-40 promoter): (1) in the "promoter" site just upstream of the SV-40 promoter; and (2) in the "enhancer" site downstream of the luciferase gene. The motif was inserted in either the forward (sense strand: 5'-ACCATAGATA-3') or reverse (sense strand: 5'-TATCTATGGT-3') orientation. Luciferase assays were performed in PC12 cells, a cell line derived from a rat adrenal medullary chromaffin cell tumor (pheochromocytoma).31

The motif significantly decreased transcriptional activity when inserted into the "promoter" position in both forward (0.50±0.04 RLU/μg protein; \( P=0.0003 \)) and reverse orientations (0.66±0.06 RLU/μg protein; \( P=0.0055 \)) compared with the control vector without motif insert (1.00±0.07 RLU/μg protein; Figure 2). There was no significant difference between luciferase activity of the promoter-forward and promoter-reverse orientation constructs. The motif did not significantly affect transcriptional activity when inserted into the "enhancer" position in either the forward (1.02±0.04 RLU/μg protein) or reverse orientations (0.94±0.07 RLU/μg protein) compared with the control vector without motif insert (1.00±0.07 RLU/μg protein; Figure 2).

**Computational Prediction of Motif/Transcription Factor Binding**

The CONSITE and P-MATCH algorithms were used to predict which transcription factors bind to the motif identified with MITRA (Table 1). CONSITE identified 6 putative transcription factors: MEF2A—myocyte enhancer factor 2A, RUNX1—runt-related transcription factor 1, SOX9—SRY-box 9, SOX17—SRY-box 17, SRY—sex-determining region Y, and YY1—yin yang 1. P-MATCH identified 4 putative transcription factors: HOXA3—homeobox A3, RUNX1, SRY, and YY1. The MEF2A, RUNX1, SOX9, and SOX17 transcription factors were also predicted to bind the SV-40 promoter, the promoter that drives expression of the pGL3-promoter vector (the control vector in the luciferase reporter promoter, the promoter that drives expression of the pGL3-promoter vector). The CONSITE and P-MATCH algorithms were used to determine if the motif conferred transcriptional activity. Because positions 8 and 10 in the motif consensus sequence (5'-ACCATAGNTN-3') lacked nucleotide preference ("N"), adenine ("A") was randomly and independently chosen to fill each "N" position in the motif (5'-ACCATAGATA-3'). The motif was inserted in 2 regions of the pGL3-promoter luciferase reporter plasmid (driven by the SV-40 promoter): (1) in the "promoter" site just upstream of the SV-40 promoter; and (2) in the "enhancer" site downstream of the luciferase gene. The motif was inserted in either the forward (sense strand: 5'-ACCATAGATA-3') or reverse (sense strand: 5'-TATCTATGGT-3') orientation. Luciferase assays were performed in PC12 cells, a cell line derived from a rat adrenal medullary chromaffin cell tumor (pheochromocytoma).31

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**Luciferase Assays: Transactivation by Transcription Factor Cotransfection**

Promoter/luciferase reporter cotransfection experiments were performed with the promoter-forward and promoter-reverse orientation constructs as well as cDNA expression plasmids for the transcription factors computationally predicted to bind the motif. One set of transcription factors (HOXA3, SRY, YY1) had no effect on the control vector at the same time as significantly increasing the expression of the promoter-forward or motif-reverse constructs (Figure 3; Table 2). More specifically, HOXA3 increased expression of the promoter-forward construct by 1.24-fold \( (P<0.05) \); SRY increased expression of the promoter-forward construct by 1.26-fold \( (P<0.05) \); and YY1 significantly increased expression of the promoter-forward construct by 1.49-fold \( (P<0.05) \) and the promoter-reverse construct by 1.63-fold \( (P<0.05) \).

Another set of transcription factors (RUNX1, SOX9, SOX17) significantly decreased expression of the insertless control vector (SV-40 promoter, pGL3-promoter) at the same time as also reducing expression of the promoter-forward and/or promoter-reverse constructs (Figure 4; Table 2). Specific changes included: RUNX1 reduced expression of the promoter-forward construct by 0.69-fold \( (P<0.05) \); SOX9 reduced expression of the promoter-forward construct by 0.64-fold \( (P<0.05) \); SOX17 reduced expression of the promoter-forward
Table 1. Transcription Factors Predicted to Bind the MITRA-Identified Motif

<table>
<thead>
<tr>
<th>Transcription Factor</th>
<th>Accession No.</th>
<th>CONSITE Score</th>
<th>P-MATCH Score</th>
<th>Strand</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOX9</td>
<td>MA0077</td>
<td>6.194</td>
<td>...</td>
<td>+</td>
</tr>
<tr>
<td>SRY</td>
<td>MA0084; R07263</td>
<td>2.695</td>
<td>0.755</td>
<td>+</td>
</tr>
<tr>
<td>YY1</td>
<td>MA0095; R05992</td>
<td>7.027</td>
<td>0.964</td>
<td>+</td>
</tr>
<tr>
<td>HOXA3</td>
<td>R07263</td>
<td>...</td>
<td>0.938</td>
<td>-</td>
</tr>
<tr>
<td>MEF2A</td>
<td>MA0052</td>
<td>5.567</td>
<td>...</td>
<td>-</td>
</tr>
<tr>
<td>RUNX1</td>
<td>MA0002; R07891</td>
<td>5.491</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>SOX17</td>
<td>MA0078</td>
<td>4.273</td>
<td>...</td>
<td>-</td>
</tr>
</tbody>
</table>

The CONSITE and P-MATCH algorithms identified a total of 7 transcription factors predicted to bind the MITRA-identified motif. Three transcription factors (RUNX1, SRY, and YY1) were identified by both algorithms. The JASPAR accession no. for CONSITE predictions and the TRANSFAC site accession for P-MATCH predictions are listed. CONSITE and P-MATCH binding scores and the DNA strand on which the transcription factor was predicted to bind are also presented.

construct by 0.73-fold (P<0.05); and the promoter-reverse construct by 0.75-fold (P<0.05). MEF2A reduced expression of the control vector by 0.77-fold (P<0.05) but had no effect on the promoter-forward or promoter-reverse constructs.

Human Blood Pressure Extremes: Statistical Genetic Associations With the Metabolic Syndrome

Initial Study
The HapMap was used to select common (minor allele frequency >5%), validated tagging SNPs that capture the linkage disequilibrium and haplotype block structure within the human HOXA3, SRY, and YY1 loci. These tagging SNPs were genotyped in a sample from extremes of blood pressure in the San Diego population (all SNPs were genotyped in cohort 1): white (European ancestry) males and females from the lowest and highest percentiles of DBP distribution (≤63 mm Hg or ≥290 mm Hg). Statistical association was tested between tagging SNPs and several traits of the human metabolic syndrome: SBP, DBP, BMI, plasma glucose, plasma total cholesterol, and plasma HDL cholesterol (Table 3).

In the first cohort, HOXA3 SNP rs10085570 showed significant association with DBP (P=0.017). The SRY-tagging SNP rs2058276 in males significantly associated with SBP (P=0.027), DBP (P=0.018), and BMI (P=0.004). YY1 SNP rs8021803 showed a significant association with both SBP (P=0.004) and DBP (P=0.002). YY1 SNP rs11625658 significantly associated with SBP (P=0.0002), DBP (P=0.0006), BMI (P=0.006), and plasma glucose (P=0.024). Multivariate analysis of variance for YY1 rs11625658 revealed significant association between YY1 genotype and the following set of metabolic syndrome traits: SBP, DBP, BMI, and plasma glucose (P=0.0005; effect size=0.012 or 1.2% for the joint set of traits; specific individual trait effect size and directionality are shown in Tables 3 and 4). No significant associations were found for plasma total cholesterol or plasma HDL cholesterol for any of the HOXA3, SRY, or YY1 SNPs.

SNPs found to be significantly associated in cohort 1 were then examined within San Diego blood pressure extreme cohort 2. Only YY1 SNP rs1625658 showed a significant association in this second cohort; HOXA3 SNP rs10085570, SRY SNP rs2058276, and YY1 SNP rs8021803 did not show significant association in cohort 2 (data not shown).

Potential interdependence of the statistical associations of SBP, DBP, BMI, and plasma glucose (4 correlated traits) with YY1 SNP rs11625658 was examined using a modified statistical model wherein the 4 traits were systematically used as covariates for each other (using the false discovery rate <0.05 multiple testing correction; age and sex remained as covariates in all analyses). In cohort 1, associations with SBP and DBP remained significant when BMI and/or plasma glucose were added as covariates; and BMI retained significance when plasma glucose was added as a covariate (data not shown).

Meta-Analysis
Because rs11625658 showed the highest degree of association in cohort 1 and preliminary association in cohort 2,
we sought to extend the results of its significant SBP, DBP, BMI, and glucose associations into 2 additional population samples: San Diego blood pressure extreme cohort 2 (n=1075) and the ICBP-GWAS (n=66741) for a total of 812 subjects (Table 4). By meta-analysis, considering the effect size (β or slope per allele) and its SE for each subgroup, we found nominally significant effects across the 3 groups for YY1 tagging variant rs11625658 on DBP (P=0.033), BMI (P=0.004), and fasting glucose (P=0.038). Inspection of β (slope) values revealed directionally consistent effects in each subgroup, although inverse allelic effects (ie, positive versus negative β-slope values) were observed for DBP and BMI. SBP and cholesterol (total or HDL) were not significantly affected in the meta-analysis observed for DBP and BMI. SBP and cholesterol (total or HDL) were not significantly affected in the meta-analysis.

**Table 2. Effect of Candidate Transcription Factors on Motif Activity**

<table>
<thead>
<tr>
<th>Transcription Factor</th>
<th>Control Vector (RLU/μg Protein)</th>
<th>Promoter-Forward (RLU/μg Protein)</th>
<th>Promoter-Reverse (RLU/μg Protein)</th>
</tr>
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<tbody>
<tr>
<td>Control: empty vector</td>
<td>1.00±0.06</td>
<td>0.74±0.04</td>
<td>0.68±0.04</td>
</tr>
<tr>
<td>No effect on control vector</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HOXA3</td>
<td>0.92±0.08</td>
<td>0.66±0.02</td>
<td>0.84±0.03‡</td>
</tr>
<tr>
<td>SRY</td>
<td>0.94±0.05</td>
<td>0.93±0.04†</td>
<td>0.79±0.04</td>
</tr>
<tr>
<td>YY1</td>
<td>0.87±0.07</td>
<td>1.10±0.06†</td>
<td>1.11±0.08‡</td>
</tr>
<tr>
<td>Effect on control vector</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MEF2A</td>
<td>0.77±0.06*</td>
<td>0.73±0.04</td>
<td>0.62±0.07</td>
</tr>
<tr>
<td>RUNX1</td>
<td>0.62±0.03*</td>
<td>0.51±0.09†</td>
<td>0.65±0.06</td>
</tr>
<tr>
<td>SOX9</td>
<td>0.69±0.09*</td>
<td>0.47±0.02†</td>
<td>0.54±0.05</td>
</tr>
<tr>
<td>SOX17</td>
<td>0.62±0.02*</td>
<td>0.54±0.02†</td>
<td>0.51±0.03‡</td>
</tr>
</tbody>
</table>

Luciferase reporter assays were performed with cotransfection of cDNA expression plasmids for transcription factors computationally predicted to bind the motif. The effects of transcription factors on the motif in the promoter position in either the forward or reverse orientation were tested. Data are presented as normalized intensity (RLU/μg protein). The pGL3-promoter vector, which contains the SV-40 promoter driving expression of the luciferase gene, served as the control luciferase expression vector. The control for the transcription factor expression plasmids was an empty vector containing only the CMV promoter. Data were analyzed with analysis of variance followed by pairwise t-tests corrected for multiple comparisons.

Microarray Expression Analysis

We began with genomewide gene expression analysis of adrenal glands from the BPH and BPL blood pressure trait extreme inbred mouse strains. Although the widespread expression changes (up to approximately 16%) were initially surprising (online-only Data Supplement Table I), they likely reflected the polygenic nature of essential hypertension, the comparison of extreme phenotypes, and the diverse adaptations or responses to disease processes. Functional clustering uncovered a striking pattern of global underexpression of intermediary metabolism pathways in the BPH (online-only Data Supplement Table II), and we hypothesized that such consistent underexpression throughout interacting and functionally related pathways resulted from a common transcriptional mechanism.

Computational Motif Identification

The MITRA algorithm identified a conserved motif in the set of transcriptional regulatory sequences from the 82 differentially
expressed genes of the intermediary metabolism subpathways (Figure 1). The motif was present in approximately half (38 of 82) of the differentially expressed genes (online-only Data Supplement Table III) in an equal proportion in each of the metabolic subpathways, suggesting that if the motif altered transcription, it was likely to be important in regulation of not only each individual subpathway but also the function of intermediary metabolism as a whole.

Determination of Motif Transcriptional Activity
Promoter/luciferase reporter assays demonstrated that the motif was functional in the promoter position, in both the forward and reverse orientations, but lacked activity in the enhancer position (in either orientation; Figure 2). Classical cis-acting proximal promoter elements are typically dependent on both strand orientation and distance from the transcriptional start site, whereas classical trans-acting enhancer

Table 3. Initial (cohort 1; n=996) associations of candidate genes with hypertension and metabolic syndrome traits

<table>
<thead>
<tr>
<th>Gene</th>
<th>RefSNP ID</th>
<th>Systolic BP</th>
<th>Diastolic BP</th>
<th>BMI</th>
<th>Plasma Glucose</th>
<th>HDL Cholesterol</th>
<th>Total Cholesterol</th>
</tr>
</thead>
<tbody>
<tr>
<td>YY1</td>
<td>rs8021803</td>
<td>P = 0.004* (1.3%)</td>
<td>P = 0.022* (1.4%)</td>
<td>P = 0.098</td>
<td>P = 0.359</td>
<td>P = 0.176</td>
<td>P = 0.065</td>
</tr>
<tr>
<td>YY1</td>
<td>rs11625658</td>
<td>P = 0.0002* (1.9%)</td>
<td>P = 0.0006* (1.6%)</td>
<td>P = 0.006* (1.2%)</td>
<td>P = 0.024* (0.9%)</td>
<td>P = 0.137</td>
<td>P = 0.281</td>
</tr>
<tr>
<td>YY1</td>
<td>rs4095941</td>
<td>P = 0.113</td>
<td>P = 0.166</td>
<td>P = 0.037</td>
<td>P = 0.636</td>
<td>P = 0.154</td>
<td>P = 0.901</td>
</tr>
<tr>
<td>SRY</td>
<td>rs2058276</td>
<td>P = 0.027* (1.5%)</td>
<td>P = 0.018* (1.7%)</td>
<td>P = 0.004* (2.3%)</td>
<td>P = 0.079</td>
<td>P = 0.191</td>
<td>P = 0.149</td>
</tr>
<tr>
<td>SRY</td>
<td>rs1865680</td>
<td>P = 0.299</td>
<td>P = 0.371</td>
<td>P = 0.113</td>
<td>P = 0.651</td>
<td>P = 0.272</td>
<td>P = 0.733</td>
</tr>
<tr>
<td>HOXA3</td>
<td>rs10085570</td>
<td>P = 0.050</td>
<td>P = 0.017* (1.0%)</td>
<td>P = 0.614</td>
<td>P = 0.879</td>
<td>P = 0.411</td>
<td>P = 0.665</td>
</tr>
<tr>
<td>HOXA3</td>
<td>rs6948297</td>
<td>P = 0.054</td>
<td>P = 0.116</td>
<td>P = 0.081</td>
<td>P = 0.973</td>
<td>P = 0.652</td>
<td>P = 0.867</td>
</tr>
</tbody>
</table>

Statistical association between candidate gene tagging single nucleotide polymorphisms (SNPs) and the following metabolic syndrome traits was tested: systolic blood pressure (BP), diastolic BP, body mass index (BMI), plasma glucose, plasma total cholesterol, and plasma high-density lipoprotein (HDL) cholesterol. Data were analyzed with univariate analysis of variance using an additive model (independent variable=diploid genotype; dependent variable=metabolic syndrome trait; covariance=age, sex). Nominal P values that satisfy a false discovery rate (0.05) correction for testing of multiple genotypes and phenotypes are indicated with an asterisk (*). The effect size (partial eta-squared [η²]: the proportion of total trait variance attributable to the specific SNP, expressed as percent of trait variance) for significant SNPs is presented in parenthesis following the P values.

Table 4. Meta-Analysis: Extension of Initial Genetic Associations Into Additional Population Samples

<table>
<thead>
<tr>
<th>YY1 RefSNP</th>
<th>Group</th>
<th>Allele_1/ Allele_2</th>
<th>Freq_A1</th>
<th>No.</th>
<th>Trait</th>
<th>Model</th>
<th>Beta (Slope, per allele)</th>
<th>SE of Beta</th>
<th>P Value From Meta-Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>rs11625658</td>
<td>Cohort 1</td>
<td>A/C</td>
<td>25.3%</td>
<td>996</td>
<td>DBP</td>
<td>Additive</td>
<td>2.180</td>
<td>1.106</td>
<td>...</td>
</tr>
<tr>
<td>rs11625658</td>
<td>Cohort 2</td>
<td>A/C</td>
<td>26.2%</td>
<td>1075</td>
<td>DBP</td>
<td>Additive</td>
<td>1.513</td>
<td>0.816</td>
<td>...</td>
</tr>
<tr>
<td>rs11625658</td>
<td>ICBP</td>
<td>A/C</td>
<td>23.3%</td>
<td>66741</td>
<td>DBP</td>
<td>Additive</td>
<td>0.140</td>
<td>0.070</td>
<td>...</td>
</tr>
<tr>
<td>rs11625658</td>
<td>Meta-analysis</td>
<td>A/C</td>
<td>...</td>
<td>68812</td>
<td>DBP</td>
<td>Additive</td>
<td>0.148</td>
<td>0.069</td>
<td>0.033*</td>
</tr>
<tr>
<td>rs11625658</td>
<td>Cohort 1</td>
<td>A/C</td>
<td>25.3%</td>
<td>996</td>
<td>SBP</td>
<td>Additive</td>
<td>2.560</td>
<td>1.373</td>
<td>...</td>
</tr>
<tr>
<td>rs11625658</td>
<td>Cohort 2</td>
<td>A/C</td>
<td>26.2%</td>
<td>1075</td>
<td>SBP</td>
<td>Additive</td>
<td>0.540</td>
<td>1.169</td>
<td>...</td>
</tr>
<tr>
<td>rs11625658</td>
<td>ICBP</td>
<td>A/C</td>
<td>23.3%</td>
<td>66741</td>
<td>SBP</td>
<td>Additive</td>
<td>0.074</td>
<td>0.110</td>
<td>...</td>
</tr>
<tr>
<td>rs11625658</td>
<td>Meta-analysis</td>
<td>A/C</td>
<td>...</td>
<td>68812</td>
<td>SBP</td>
<td>Additive</td>
<td>0.052</td>
<td>0.109</td>
<td>0.634</td>
</tr>
<tr>
<td>rs11625658</td>
<td>Cohort 1</td>
<td>A/C</td>
<td>25.3%</td>
<td>996</td>
<td>BMI</td>
<td>Additive</td>
<td>1.217</td>
<td>0.405</td>
<td>...</td>
</tr>
<tr>
<td>rs11625658</td>
<td>Cohort 2</td>
<td>A/C</td>
<td>26.2%</td>
<td>1075</td>
<td>BMI</td>
<td>Additive</td>
<td>0.415</td>
<td>0.303</td>
<td>...</td>
</tr>
<tr>
<td>rs11625658</td>
<td>Meta-analysis</td>
<td>A/C</td>
<td>...</td>
<td>2071</td>
<td>BMI</td>
<td>Additive</td>
<td>0.703</td>
<td>0.242</td>
<td>0.004*</td>
</tr>
<tr>
<td>rs11625658</td>
<td>Cohort 1</td>
<td>A/C</td>
<td>25.3%</td>
<td>996</td>
<td>Glucose</td>
<td>Additive</td>
<td>2.776</td>
<td>1.069</td>
<td>...</td>
</tr>
<tr>
<td>rs11625658</td>
<td>Cohort 2</td>
<td>A/C</td>
<td>26.2%</td>
<td>1075</td>
<td>Glucose</td>
<td>Additive</td>
<td>0.311</td>
<td>1.129</td>
<td>...</td>
</tr>
<tr>
<td>rs11625658</td>
<td>Meta-analysis</td>
<td>A/C</td>
<td>...</td>
<td>2071</td>
<td>Glucose</td>
<td>Additive</td>
<td>1.661</td>
<td>0.802</td>
<td>0.038*</td>
</tr>
<tr>
<td>rs11625658</td>
<td>Cohort 1</td>
<td>A/C</td>
<td>25.3%</td>
<td>996</td>
<td>HDL chol</td>
<td>Additive</td>
<td>0.589</td>
<td>0.821</td>
<td>...</td>
</tr>
<tr>
<td>rs11625658</td>
<td>Cohort 2</td>
<td>A/C</td>
<td>26.2%</td>
<td>1075</td>
<td>HDL chol</td>
<td>Additive</td>
<td>0.098</td>
<td>0.619</td>
<td>0.874</td>
</tr>
<tr>
<td>rs11625658</td>
<td>Meta-analysis</td>
<td>A/C</td>
<td>...</td>
<td>2071</td>
<td>HDL chol</td>
<td>Additive</td>
<td>1.28</td>
<td>2.015</td>
<td>...</td>
</tr>
<tr>
<td>rs11625658</td>
<td>Cohort 1</td>
<td>A/C</td>
<td>25.3%</td>
<td>996</td>
<td>Total chol</td>
<td>Additive</td>
<td>−1.559</td>
<td>1.968</td>
<td>...</td>
</tr>
<tr>
<td>rs11625658</td>
<td>Cohort 2</td>
<td>A/C</td>
<td>26.2%</td>
<td>1075</td>
<td>Total chol</td>
<td>Additive</td>
<td>−0.173</td>
<td>1.407</td>
<td>0.902</td>
</tr>
</tbody>
</table>

Meta-analysis was conducted in STATA using fixed-effect models. Individual regression models were additive. Effect sizes (from regression) are given as beta (or slope per allele), ±SE of β. Significant effects (P<0.05) are indicated with an asterisk (*).

SNP indicates single nucleotide polymorphism; Cohort 1 and Cohort 2, independent samples from the extremes of a large primary care population; ICBP, International Collaboration on Blood Pressure Genome Wide Association Study; DBP, diastolic blood pressure; SBP, systolic blood pressure; BMI, body mass index; HDL, high-density lipoprotein; chol, cholesterol.
elements are independent of orientation and distance. If we assume the binding of only one transcription factor to the motif, the distance-dependent yet orientation-independent activity of the motif could represent an alternative mode of action for proximal promoter elements. It is also conceivable that the motif consensus sequence represents a composite of ≥2 distinct motifs with each one directing binding of different transcription factors in either the forward or reverse orientation.

**Transcription Factor Identification**

We then queried TRANSFAC and JASPAR to identify transcription factors that might bind the motif and, therefore, regulate its cis-acting transcriptional activity (Table 1). Expression plasmids for these transcription factors (HOXA3, MEF2A, RUNX1, SOX9, SOX17, SRY, and YY1) were cotransfected with the luciferase reporter constructs (with the motif inserted only in the promoter position) to determine which transcription factors could modulate transcription through the motif.

One important caveat of the luciferase experiments was that both the control vector (without motif insert) and the promoter-forward and -reverse constructs (with the motif insert) contained the SV-40 promoter (in pGL3-promoter) to direct basal eukaryotic transcription. Transcription factor effects on the motif were therefore difficult to distinguish from effects on the SV-40 promoter if transcriptional activity was altered in both the control vector (pGL3-promoter) and in the motif promoter-forward or -reverse constructs; such was the case for RUNX1, SOX9, and SOX17, which significantly decreased expression of both the control vector and the promoter-forward and/or promoter-reverse constructs (Figure 4; Table 2). Computational analysis of the SV-40 promoter revealed that both the control vector (without motif insert) and the promoter-forward or -reverse constructs; such was the case for RUNX1, SOX9, and SOX17 binding sites, so their effects on the control vector were not unexpected.

Thus HOXA3, SRY, and YY1 emerged as the strongest candidates for transcriptional regulation of the motif, because they altered luciferase expression of the motif-containing constructs but lacked effects on the control vector (without a motif insert; Figure 3; Table 2). These 3 candidate transcription factors had distinct patterns of regulation: HOXA3 had no effect on the promoter-forward construct but increased expression of the promoter-reverse construct; SRY increased expression of the promoter-forward but had no effect on the promoter-reverse construct; YY1 increased expression of both the promoter-forward and the promoter-reverse constructs. It is conceivable that the motif consensus sequence might form a composite of HOXA3, SRY, and YY1 motifs, wherein binding specificity to target genes in vivo is dictated by strand orientation, deviation of the actual motif sequence from the consensus (shown in online-only Data Supplement Table III), and the relative abundance and/or activity of endogenous HOXA3, SRY, YY1, and their cofactors in the nucleus.

There is a precedent that inbred rodent models of genetic hypertension such as the BPH exhibit metabolic abnormalities. The spontaneously hypertensive rat (SHR), the most widely studied inbred model of genetic hypertension, was developed in a selection paradigm similar to that of the BPH (ie, selection only on the basis of elevated blood pressure), yet the SHR also exhibits dyslipidemia and insulin resistance and is widely studied as model of the metabolic syndrome. Although the BPH has not been as thoroughly investigated as SHR as a model of the metabolic syndrome, the BPH strain exhibits several metabolic abnormalities, including decreased plasma HDL cholesterol, enhanced rate of body weight gain on a high-fat diet, and increased pulse rate. Perhaps pleiotropic genetic variants that affect both blood pressure and metabolism were fixed during the blood pressure selection program for the BPH. If such “master switches” exist, transcription factors (such as HOXA3, SRY, and YY1) would be logical and indeed compelling candidates. Because we identified HOXA3, SRY, and YY1 as candidate transcriptional regulators of perturbed intermediary metabolism in an inbred rodent model of human genetic hypertension, we hypothesized that blood pressure and other metabolic syndrome traits in humans might stem from genetic variation in the HOXA3, SRY, and YY1 loci.

**Human SNP Genotyping and Statistical Genetic Association**

We then genotyped common HapMap tagging SNPs that captured the linkage disequilibrium structure within the human HOXA3, SRY, and YY1 loci. These tagging SNPs were located in noncoding regions (ie, upstream of the gene or within an intron) of our candidate genes. Statistical association of the SNPs with several traits of the metabolic syndrome was tested in a sample of population blood pressure extremes (white males and females from the lowest and highest percentiles of DBP distribution). Although our blood pressure extreme groups were ascertained on a DBP criterion, recent evidence indicates that SBP is at least as important a risk factor for target organ damage; we plan future studies to explore the potential effect of polymorphism in isolated systolic hypertension.

Transcription factor YY1 emerged as the most compelling candidate gene for the human metabolic syndrome. In the BPH, YY1 was differentially expressed across both age groups (in juvenile prehypertensives and adult hypertensives) as well as in only the juvenile hypertensives (data not shown). In cohort 1, YY1 SNP rs11625658 significantly associated with not only blood pressure (SBP: $P=0.0002$; DBP: $P=0.0006$), but also BMI ($P=0.006$) and carbohydrate metabolism (plasma glucose: $P=0.024$), although not with lipid metabolism (neither plasma total cholesterol nor plasma HDL cholesterol; Table 3). Furthermore, multivariate analysis of variance demonstrated that rs11625658 genotype significantly associated with SBP, DBP, BMI, and plasma glucose as a joint set of traits ($P=0.0005$). Finally, meta-analysis (Table 4) indicated that the YY1 variant rs11625658 continued to predict DBP, BMI, and glucose in a very large number of subjects ($n=up to 68,812$) with unexpectedly inverse (or opposite) allelic effects on DBP and BMI. Studies of rs11625658 in additional human populations would bolster YY1 as a candidate gene for hypertension and the metabolic syndrome.

YY1 is a ubiquitous, multifunctional zinc-finger transcription factor with fundamental roles in biological processes such as embryogenesis, differentiation, cellular proliferation, and cell-cycle progression. Indeed, homozygous knockout of the YY1 gene is lethal. The actions of YY1 are complex, because the transcription factor can directly or indirectly
(through cofactors) activate or repress transcription and can also disrupt binding sites by changing DNA conformation. For example, YY1 regulates expression of p53 and a transcription factor and tumor suppressor that controls cell-cycle progression and the cellular stress response. Adipose YY1, a transcription factor and tumor suppressor that controls cell-cycle progression and the cellular stress response. YY1 could modulate multiple metabolic syndrome traits (eg, SBP, DBP, BMI, and plasma glucose) through a network of direct or indirect gene-by-gene or protein–protein (transcription factor) interactions.

Genetic variation at the YY1 locus in rats is associated with development of Type 1 diabetes, potentially through its actions on cytokine-related genes. In mice, YY1 gene expression significantly correlates with cardiovascular function, specifically the P-R wave interval of an electrocardiogram. In addition, two quantitative trait loci for body weight and urinary albumin excretion in the rat have been mapped to the YY1-containing region of the human genome using stringently filtered cross-species alignments. Knockout mice expressing graded amounts of YY1 (75%, 50%, 25%) displayed dose-dependent changes in sensitivity to apoptosis, a key component of target organ damage in hypertension. RNA interference strategies have been used to generate transgenic mouse lines that express reduced levels of YY1 protein and exhibit decreased birth weight and size. Functional genetic variation at the YY1 locus could thereby provide a unifying genetic mechanism for a portion of metabolic syndrome trait variation in the population.

Conclusions and Perspectives

We developed a novel sequential strategy for identification of candidate genes in the cardiometabolic syndrome. The method integrated several disciplines and tools (animal models, microarray technology, bioinformatics, molecular biology, extreme phenotypes, human genetics) and suggested a previously unexplored gene, YY1, as a candidate and potential mechanistic link for several traits of the human metabolic syndrome. Thus, development of novel methods to identify candidate genes might prove advantageous in the quest to understand the genetic basis of complex traits.

Acknowledgments

The authors thank the International Consortium for Blood Pressure Genome Wide Association Studies (ICBP-GWAS) for the data they contributed to this study.

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Disclosure

None.

References

We developed a novel, integrative method (combining animal models, transcriptomics, bioinformatics, molecular biology, disorders known as the cardiometabolic syndrome. It is unclear if these phenotypes share common genetic contributors. tension often clusters with metabolic abnormalities, which themselves also have genetic underpinnings, in a collection of candidate gene “master switch.”

for multiple phenotypes of the cardiometabolic syndrome and specifically point to transcription factor YY1 as a potential preserved on diastolic blood pressure, body mass index, and fasting glucose. The results suggest shared genetic contributors single nucleotide polymorphism rs11625658 on systolic blood pressure, diastolic blood pressure, body mass index, and significantly associated in a human population blood pressure extreme sample with the most extensive associations for might predict blood pressure and other cardiometabolic syndrome traits in humans. Genetic variants for each locus were of a murine model of genetic hypertension led us to hypothesize that genetic variation at the transcription factors as “master switches” because functional changes in them are likely to be pleiotropic and, therefore, might provide a unifying genetic mechanism for multiple traits. A transcriptomic, bioinformatic, and molecular biological analysis transcription factors as “master switches” because functional changes in them are likely to be pleiotropic and, therefore, might provide a unifying genetic mechanism for multiple traits. A transcriptomic, bioinformatic, and molecular biological analysis of a murine model of genetic hypertension led us to hypothesize that genetic variation at the HOXA3, SRY, and YY1 loci might predict blood pressure and other cardiometabolic syndrome traits in humans. Genetic variants for each locus were significantly associated in a human population blood pressure extreme sample with the most extensive associations for YY1 single nucleotide polymorphism rs11625658 on systolic blood pressure, diastolic blood pressure, body mass index, and fasting glucose. Meta-analysis extended the YY1 results into 2 additional large population samples with significant effects preserved on diastolic blood pressure, body mass index, and fasting glucose. The results suggest shared genetic contributors for multiple phenotypes of the cardiometabolic syndrome and specifically point to transcription factor YY1 as a potential candidate gene “master switch.”

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Integrated Computational and Experimental Analysis of the Neuroendocrine Transcriptome in Genetic Hypertension Identifies Novel Control Points for the Cardiometabolic Syndrome

Ryan S. Friese, Chun Ye, Caroline M. Nievergelt, Andrew J. Schork, Nitish R. Mahapatra, Fangwen Rao, Philip S. Napolitan, Jill Waalen, Georg B. Ehret, Patricia B. Munroe, Geert W. Schmid-Schönbein, Eleazar Eskin and Daniel T. O'Connor

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The Implications of Inheritance for Clinical Management: Supplemental Material

Srijita Sen-Chowdhry, MBBS, MD, FESC, Daniel Jacoby, MD, William J. McKenna, MD, DSc, FESC

**Estimating Heritability**

Quantifying heritability in a population therefore depends on the partitioning of observed phenotypic variation (σ_p) into unobserved genetic (σ_G) and environmental (σ_E) factors. The genetic variance can be further subdivided into the variance of additive genetic effects (σ_A), of dominance genetic effects (interactions between alleles at the same locus, σ_D), and of epistatic genetic effects (interactions between alleles at different loci, σ_I): σ_G = σ_A + σ_D + σ_I (Figure 3). Broad sense heritability H^2 is the ratio of the total genetic variance to the total phenotypic variance (σ_G / σ_p), whereas narrow sense heritability h^2 is the ratio of the additive genetic variance to the total phenotypic variance (σ_A / σ_p)^1.

**Figure 3. Illustrative pedigree from a large family with hypertension, a complex trait associated with multiple susceptibility loci.**

In this example, we hypothesise that four genes, A-D, control variation in systolic blood pressure in the family. The major allele of each gene is represented by the capital letter (A-D), while the lower case letter (a-d) denotes the minor allele, with lower frequency in the general population. We arbitrarily quantify the contribution of each allele to the variation in systolic blood pressure as follows: A, 1; a, 2; B, 1; b, 3; C, 2; c, 3; D, 1; d, 4.
The genotypes of the relatives in the box in Figure 3 are shown below (subscript m, p – maternal and paternal alleles respectively):

Father: Aa bb cc Dd  
Mother: Aa BB Cc DD  
Son (IV.9): A_m A_p B_m b_p C_m c_p D_m d_p  
Son (IV.10): A_m A_p B_m b_p C_m c_p D_m d_p  
Son (IV.11): A_m A_p B_m b_p C_m c_p D_m D_p  
Daughter (IV.12): A_m A_p B_m b_p C_m c_p D_m D_p

Additive model
In an additive model, the combined effect of genetic alleles at two or more gene loci is equal to the sum of their individual effects. In the father, this amounts to 20 (i.e., 1+2+3+3+3+3+1+4). The combined genetic effect for the other relatives in Box-1 will be as follows: Mother, 12; Son (IV.9), 18; Son (IV.10), 18; Son (IV.11), 10; Daughter (IV.12), 12. We can further hypothesise that a total genetic effect exceeding 15 will be associated with clinical hypertension; consequently, the father and two older sons are hypertensive, while the remaining family members are normotensive.

Dominance model
Alleles that exhibit a dominant action will mask the contribution of recessive partners at the same locus. For simplicity, let us assume that the major allele at each locus is dominant over its minor partner. In this model, the combined genetic effect of Aa is 2 (i.e., 1+1), equivalent to the homozygous dominant genotype AA. The combined genetic effect for the relatives in Box-1 will be: Father, 16; Mother, 10; Son (IV.9), 12; Son (IV.10), 12; Son (IV.11), 10; Daughter, 10. If we further hypothesise that a total genetic effect exceeding 11 will be associated with clinical hypertension, then the father and two older sons will be affected while other family members are not, consistent with the status depicted on the pedigree.

Of note, dominance genetic effects have no influence on phenotypic resemblance between generations. Both the father and the two older sons have hypertension, for example, because of the shared a, b, c, and d alleles. Similarly, both the mother and the youngest son are normotensive because of the shared B, C, and D alleles. Since the children can inherit only one allele at each locus from each parent, interallelic interactions do not factor into intergenerational similarities. Dominance effects may, however, contribute to phenotypic resemblance between siblings. Both the youngest son and daughter are normotensive and share the BbCc genotype, with the B and C alleles dominant over their minor partners.

Epistasis model
Phenotypic expression of a gene may be modified, suppressed, or enhanced by genes at other loci in a phenomenon known as epistasis. As an example, we hypothesise the DD genotype has an inhibitory effect (-2) on the B/b locus. Assuming otherwise additive inheritance, the combined genetic effect for the relatives in Box-1 will be: Father, 20; Mother, 10; Son (IV.9), 18; Son (IV.10), 18; Son (IV.11), 12; Daughter, 12.
Empirical studies of genetic variance components show that additive variance typically accounts for over half, and frequently almost all, of the total genetic variance, even if non-additive effects are operating at the level of gene action. For dominant genetic effects to contribute to intrafamilial phenotypic resemblance, the relatives must share both alleles at any particular locus, which is true only of full siblings; since parents transmit only a single copy of each gene to their children, interactions of this type cannot come into play between generations, where selection pressures are at work. Narrow sense heritability is therefore the more frequently cited and reproducible parameter. Conventional heritability studies include simple functions of the regression of offspring on parental phenotypes, or correlation of offspring/parental phenotypes, full/half siblings, and monozygotic/dizygotic twin pairs. A linear mixed model is generally optimal for unbalanced designs that incorporate continuous phenotypic measures from individuals with a mixture of relationships, within and across multiple generations. One approach for binary traits, such as disease status, is to parameterise familial resemblance on a continuous liability scale so that the heritability is independent of disease prevalence.

“Missing Heritability” of Complex Traits

Variants of low minor allele frequency (MAF), defined here as ~0.5-5%, or rare variants (MAF < 0.5%) are not captured by current GWA genotyping arrays. Neither are their effect sizes large enough to allow consistent detection by classical linkage analysis in family studies. Direct sequencing may therefore be necessary to assess the contribution of infrequent genetic variants to complex traits. Mendelian disorders at the extremes of the phenotypic spectrum may provide candidate genes. Bartter’s and Gitelman’s syndromes, for example, are recessive Mendelian diseases associated with renal salt wasting and hypotension, with a respective prevalence of 1/ million and 1/ 40,000 in the general population. The heterozygous disease alleles have an estimated prevalence of ~1%. Screening of the Framingham Heart Study participants for variation in three of the genes implicated in these disorders (SLC12A3 (NCCT), SLC12A1 (NKCC2) and KCNJ1 (ROMK)) revealed a number of rare, heterozygous mutations, which were associated with clinically significant blood pressure reduction and protection from the development of hypertension.

Rare sequence variants also contribute to variation in plasma HDL and triglyceride levels in the general population. It has been argued that genes subject to purifying selection may show a preponderance of rare independent mutations rather than common functional variants. Mathematical modelling, however, suggests that if the susceptibility genotypes are rare (e.g., frequencies of ≤ 1 in 5,000), then very large numbers of genes (n=183-556) are needed to explain 50% of a common disease in the population, even with high individual risk ratios (RR= 10-20). In contrast, only 10-50 genes are required to explain 50% of the burden of a common disease in the population if the predisposing genotypes are common (frequencies of 10-50%), even with a risk ratio as low as 1.2. Large scale whole genome sequencing studies are awaited to further define the role of infrequent variants, and establish whether they account for the residual heritability of complex traits.

In the interim, an algorithm for estimating the proportion of all SNPs in GWA studies for a quantitative trait has shed light on the source of the “missing heritability”. The combination of linear model analysis and simulations for validation was first applied to adult height. Although highly significant and well-replicated SNPs accounted for only ~5% of the variance in height, common SNPs in total explained a further 40%.

Application of the same algorithm, modified for binary traits, to case control studies demonstrated that a substantial proportion of variation in susceptibility to Crohn’s disease and type-1 diabetes was tagged by common SNPs. Much of the “missing heritability” was therefore not missing. Returning to height as an example, more than 80% of the variation due to SNPs had gone undetected in published studies because the effects of the SNPs were too modest to reach the stringent level for genome-wide significance.
The results further suggested that the discrepancy between the 80% heritability of height and the 45% explained by SNPs was a corollary of incomplete linkage disequilibrium between contributory variants and SNPs. This in turn might be due to the residual contributory variants having a lower MAF, on average, than the SNPs typed on the array, although it was not necessary to invoke very low frequency variants (MAF < 0.001) to account for the outstanding heritability. More recently, a set of tools has been developed to estimate the total number of susceptibility loci and the distribution of their effect sizes for a trait based on discoveries from previous GWA studies. By integrating power over the predicted unidentified susceptibility loci, accounting for relative risk and allele frequency, the algorithms also estimate the expected number of discoveries for future GWA studies and the requisite sample sizes. The initial test cases were height, Crohn’s disease, and breast, prostate, and colorectal cancers; the results suggested that each trait was likely to harbour additional loci within the spectrum of low-penetrance common variants.

2 Hill WG, Goddard ME, Visscher PM. Data and theory point to mainly additive genetic variance for complex traits. PLoS Genet. 2008;4:e1000008