

¹ Transcripts with high distal heritability mediate genetic effects on
² complex metabolic traits

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⁴ Anna L. Tyler, J. Matthew Mahoney, Mark P. Keller, Candice N. Baker, Margaret Gaca, Anuj Srivastava,
⁵ Isabela Gerdes Gyuricza, Madeleine J. Braun, Nadia A. Rosenthal, Alan D. Attie, Gary A. Churchill and
⁶ Gregory W. Carter

⁷ **Abstract**

⁸ Although many genes are subject to local regulation, recent evidence suggests that complex distal regulation
⁹ may be more important in mediating phenotypic variability. To assess the role of distal gene regulation in
¹⁰ complex traits, we combined multi-tissue transcriptomes with physiological outcomes to model diet-induced
¹¹ obesity and metabolic disease in a population of Diversity Outbred mice. Using a novel high-dimensional
¹² mediation analysis, we identified a composite transcriptome signature that summarized genetic effects on
¹³ gene expression and explained 30% of the variation across all metabolic traits. The signature was heritable,
¹⁴ interpretable in biological terms, and predicted obesity status from gene expression in an independently
¹⁵ derived mouse cohort and multiple human studies. Transcripts contributing most strongly to this composite
¹⁶ mediator frequently had complex, distal regulation distributed throughout the genome. These results suggest
¹⁷ that trait-relevant variation in transcription is largely distally regulated, but is nonetheless identifiable,
¹⁸ interpretable, and translatable across species.

¹⁹ **Introduction**

²⁰ Evidence from genome-wide association studies (GWAS) suggests that most heritable variation in complex
²¹ traits is mediated through regulation of gene expression. The majority of trait-associated variants lie
²² in gene regulatory regions^{1–7}, suggesting a relatively simple causal model in which a variant alters the
²³ homeostatic expression level of a nearby (local) gene which, in turn, alters a trait. Statistical methods such
²⁴ as transcriptome-wide association studies (TWAS)^{8–11} and summary data-based Mendelian randomization
²⁵ (SMR)¹⁰ have used this idea to identify genes associated with multiple disease traits^{12–15}. However, despite

26 the great promise of these methods, explaining trait effects with local gene regulation has been more difficult
27 than initially assumed^{16;17}. Although trait-associated variants typically lie in non-coding, regulatory regions,
28 these variants often have no detectable effects on gene expression¹⁶ and tend not to co-localize with expression
29 quantitative trait loci (eQTLs)^{17;18}. These observations suggest that the relationship among genetic variants,
30 gene expression, and organism-level traits is more complex than the simple, local model.

31 In recent years the conversation around the genetic architecture of common disease traits has been addressing
32 this complexity, and there is increased interest in more distant (distal) genetic effects as potential drivers
33 of trait variation^{18–20;15;21}. In general, distal effects are defined as being greater than 4 or 5Mb away from
34 the transcription start site of a given gene. We use the terms local and distal rather than *cis* and *trans*
35 because *cis* and *trans* have specific biochemical meanings²², whereas local and distal are defined only by
36 genomic position. The importance of distal genetic effects is proposed in the omnigenic model, which posits
37 that trait-driving genes are cumulatively influenced by many distal variants. In this view, the heritable
38 transcriptomic signatures driving clinical traits are an emergent state arising from the myriad molecular
39 interactions defining and constraining gene expression. Consistent with this view, it has been suggested
40 that part of the difficulty in explaining trait variation through local eQTLs may arise in part because gene
41 expression is not measured in the appropriate cell types¹⁶, or cell states²³, and thus local eQTLs influencing
42 traits cannot be detected in bulk tissue samples. This context dependence emphasizes the essential role of
43 complex regulatory and tissue networks in mediating variant effects. The mechanistic dissection of complex
44 traits in this model is more challenging because it requires addressing network-mediated effects that are
45 weaker and greater in number. However, the comparative importance of distal effects over local effects is
46 currently only conjectured and extremely challenging to address in human populations.

47 To assess the role of wide-spread distal gene regulation in the genetic architecture of complex traits, we used
48 genetically diverse mice as a model system. In mice we can obtain simultaneous measurements of the genome,
49 transcriptome, and phenome in all individuals. We used diet-induced obesity and metabolic disease as an
50 archetypal example of a complex trait. In humans, these phenotypes are genetically complex with hundreds of
51 variants mapped through GWAS^{24;25} that are known to act through multiple tissues^{26;27}. Likewise in mice,
52 metabolic traits are also genetically complex²⁸ and synteny analysis implicates a high degree of concordance
53 in the genetic architecture between species^{28;12}. Furthermore, in contrast to humans, in mice we have access
54 to multiple disease-relevant tissues in the same individuals with sufficient numbers for adequate statistical
55 power.

56 We generated two complementary data sets: a discovery data set in a large population of Diversity Outbred
57 (DO) mice²⁹, and an independent validation data set derived by crossing inbred strains from the Collaborative

58 Cross (CC) recombinant inbred lines³⁰ to form CC recombinant inbred intercross (CC-RIX) mice. Both
59 populations were maintained on a high-fat, high-sugar diet to model diet-induced obesity and metabolic
60 disease¹².

61 The DO population and CC recombinant inbred lines were derived from the same eight inbred founder
62 strains: five classical lab strains and three strains more recently derived from wild mice²⁹, representing three
63 subspecies and capturing 90% of the known variation in laboratory mice³¹. The DO mice are maintained
64 with a breeding scheme that ensures equal contributions from each founder across the genome thus rendering
65 almost the whole genome visible to genetic inquiry and maximizing power to detect eQTLs²⁹. The CC mice
66 were initially intercrossed to recombine the genomes from all eight founders, and then inbred for at least 20
67 generations to create recombinant inbred lines^{30;32;31}. Because these two populations have common ancestral
68 haplotypes but highly distinct kinship structure, we could directly and unambiguously compare the local
69 genetic effects on gene expression at the whole-transcriptome level while varying the population structure
70 driving distal regulation.

71 In the DO population, we paired clinically relevant metabolic traits, including body weight and plasma levels
72 of insulin, glucose and lipids¹², with transcriptome-wide gene expression in four tissues related to metabolic
73 disease: adipose tissue, pancreatic islets, liver, and skeletal muscle. We measured similar metabolic traits
74 in a CC-RIX population and gene expression from three of the four tissues used in the DO: adipose tissue,
75 liver, and skeletal muscle. Measuring gene expression in multiple tissues is critical to adequately assess the
76 extent to which local gene regulation varies across the tissues and whether such variability might account for
77 previous failed attempts to identify trait-relevant local eQTLs. The CC-RIX carry the same founder alleles
78 as the DO. Thus, local gene regulation is expected to match between the populations. However, because
79 the alleles are recombined throughout the genome, distal effects are expected to vary from those in the DO,
80 allowing us to directly assess the role of distal gene regulation in driving trait-associated transcript variation.
81 To mechanistically dissect distal effects on metabolic disease, we developed a novel dimension reduction
82 framework called high-dimensional mediation analysis (HDMA) to identify the heritable transcriptomic
83 signatures driving trait variation, which we compared between mouse populations and to human data sets
84 with measured adipose gene expression. Together, these data enable a comprehensive view into the genetic
85 architecture of metabolic disease.

86 **Results**

87 **Genetic variation contributed to wide phenotypic variation**

88 Although the environment was consistent across the DO mice, the genetic diversity present in this population
89 resulted in widely varying distributions across physiological measurements (Fig. 1). For example, body
90 weights of adult individuals varied from less than the average adult C57BL/6J (B6) body weight to several
91 times the body weight of a B6 adult in both sexes (Males: 18.5 - 69.1g, Females: 16.0 - 54.8g) (Fig. 1A).
92 Fasting blood glucose (FBG) also varied considerably (Fig. 1B), although few of the animals had FBG levels
93 that would indicate pre-diabetes (19 animals, 3.8%), or diabetes (7 animals, 1.4%) according to previously
94 developed cutoffs (pre-diabetes: $\text{FBG} \geq 250 \text{ mg/dL}$, diabetes: $\text{FBG} \geq 300 \text{ mg/dL}$)³³. Males had higher
95 FBG than females on average (Fig. 1C) as has been observed before suggesting either that males were more
96 susceptible to metabolic disease on the high-fat, high-sugar (HFHS) diet, or that males and females may
97 require different thresholds for pre-diabetes and diabetes.

98 Body weight was strongly positively correlated with food consumption (Fig. 1D $R^2 = 0.51, p < 2.2 \times 10^{-16}$)
99 and FBG (Fig. 1E, $R^2 = 0.21, p < 2.2 \times 10^{-16}$) suggesting a link between behavioral factors and metabolic
100 disease. However, the heritability of this trait and others (Fig. 1F) indicates that genetics contribute
101 substantially to correlates of metabolic disease in this population.

102 The trait correlations (Fig. 1G) showed that most of the metabolic trait pairs were only modestly correlated,
103 which, in conjunction with the trait decomposition (Supp. Fig. S1), suggests complex relationships among
104 the measured traits and a broad sampling of multiple heritable aspects of metabolic disease including overall
105 body weight, glucose homeostasis, and pancreatic function.

106 **Distal Heritability Correlated with Phenotype Relevance**

107 To comprehensively assess the genetic control of gene expression in metabolic disease we measured overall
108 gene expression via bulk RNA-Seq in adipose, islet, liver, and skeletal muscle in the DO cohort (Supp. Fig.
109 S2). We performed eQTL analysis using R/qtL2³⁴ (Methods) and identified both local and distal eQTLs for
110 transcripts in each of the four tissues (Supp. Fig. S2B-E). Significant local eQTLs far outnumbered distal
111 eQTLs (Supp. Fig. S2F) and tended to be shared across tissues (Supp. Fig. S2G) whereas the few significant
112 distal eQTLs we identified tended to be tissue-specific (Supp. Fig. S2H)

113 We estimated the heritability of each transcript in terms of local and all non-local (distal) genetic factors
114 (Methods). Overall, local and distal genetic factors contributed approximately equally to transcript abundance.

115 In all tissues, both local and distal factors explained between 8 and 18% of the variance in the median

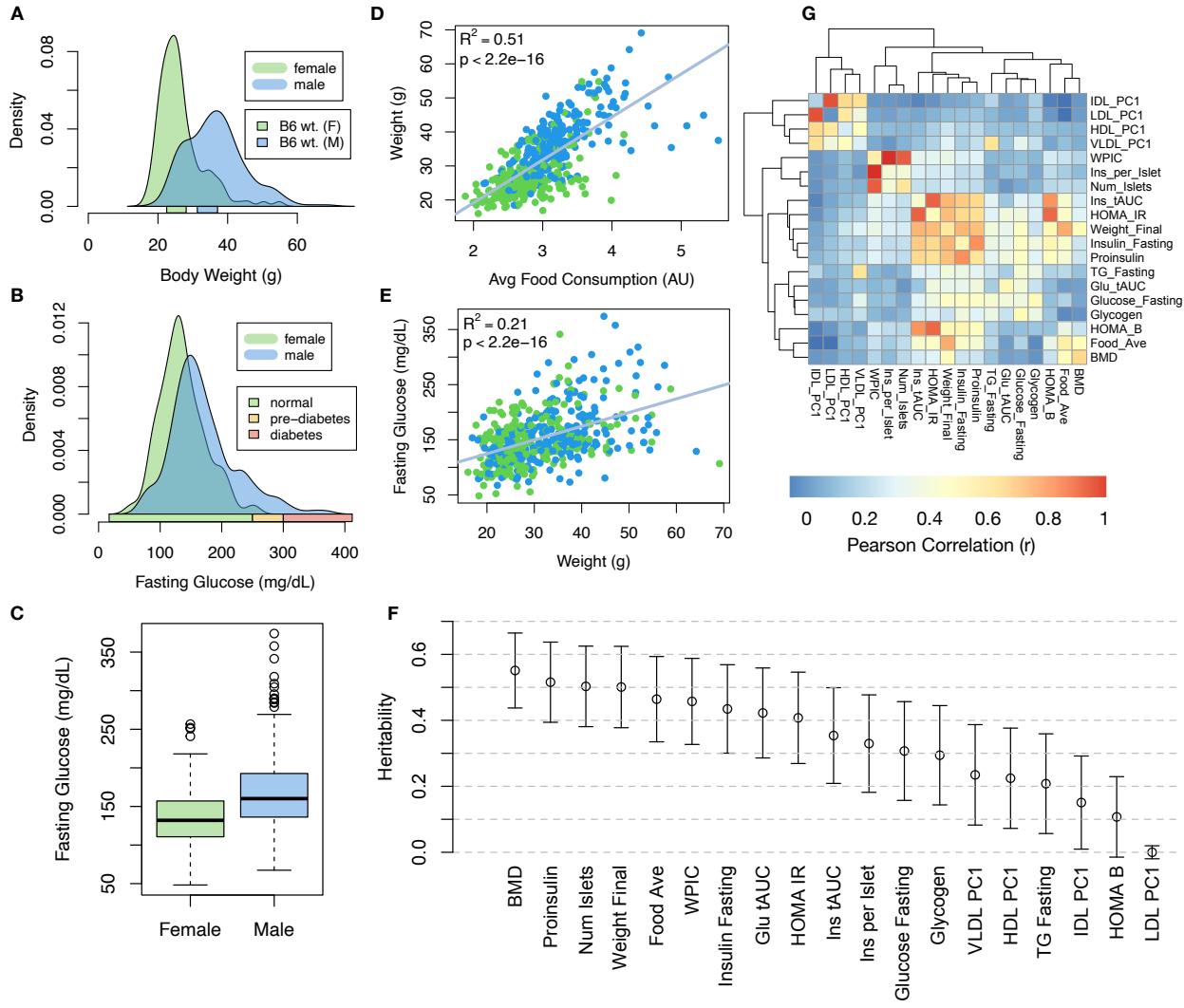


Figure 1: Clinical overview. **A.** Distributions of body weight in the diversity outbred mice. Sex is indicated by color. The average B6 male and female adult weights at 24 weeks of age are indicated by blue and green bars on the x-axis. **B.** The distribution of fasting glucose across the population split by sex. Normal, pre-diabetic, and diabetic fasting glucose levels for mice are shown by colored bars along the x-axis. **C.** Males had higher fasting blood glucose on average than females. **D.** The relationship between food consumption and body weight for both sexes. **E.** Relationship between body weight and fasting glucose for both sexes. **F.** Heritability estimates for each physiological trait. Bars show standard error of the estimate. **G.** Correlation structure between pairs of physiological traits. The diagonal of the heat map shows individual trait heritability. BMD - bone mineral density, WPIC - whole pancreas insulin content, Glu tAUC - glucose total area under the curve, HOMA IR - homeostatic measurement of insulin resistance, HOMA B - homeostatic measure of beta cell health, VLDL - very low-density lipoprotein, LDL - low-density lipoprotein, IDL - intermediate density lipoprotein, HDL - high-density lipoprotein, TG - triglyceride.

transcript (Fig. 2A).

To assess the importance of genetic regulation of transcript levels to clinical traits, we compared the local and distal heritabilities of transcripts to their trait relevance, defined as the maximum trait correlation for

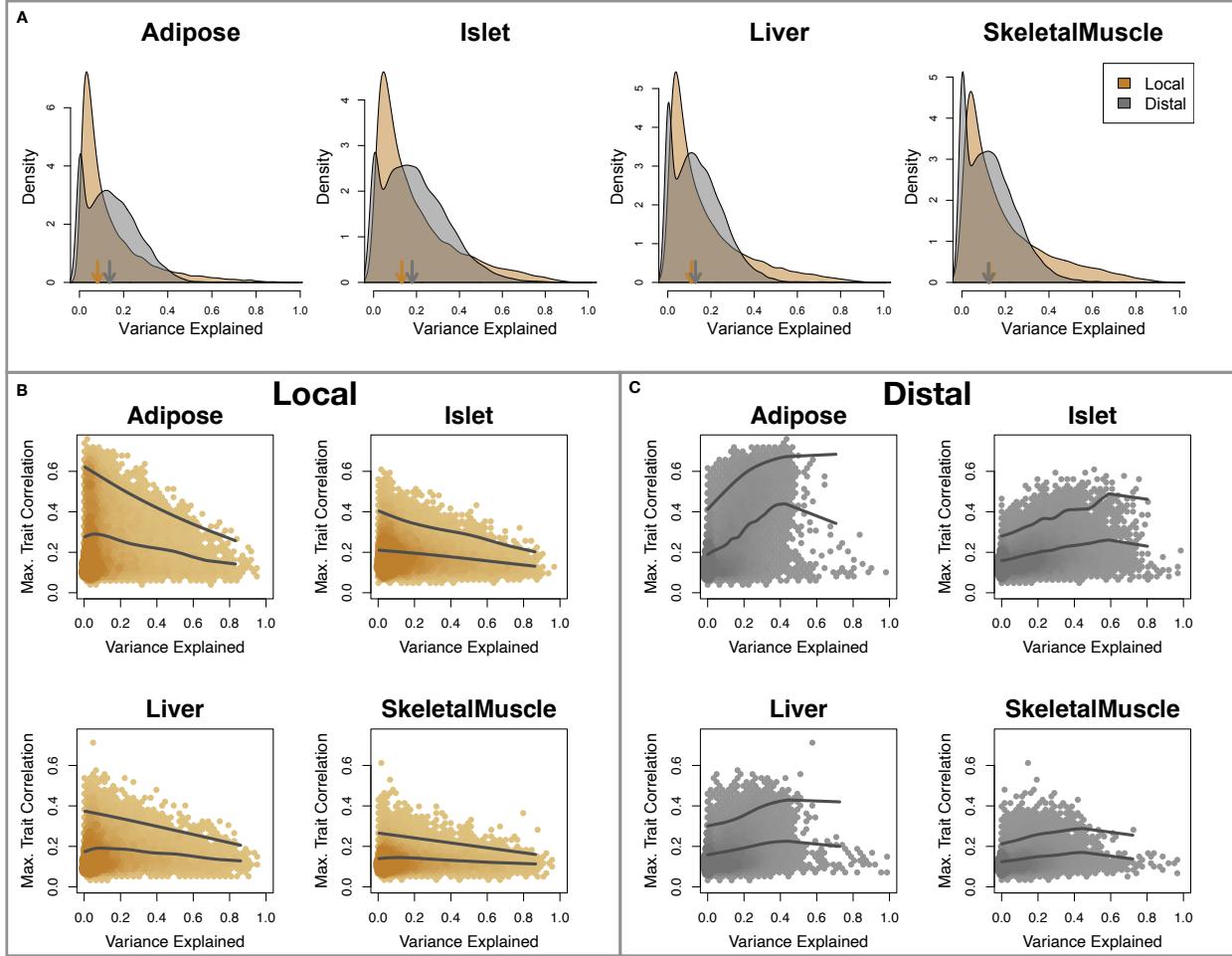


Figure 2: Transcript heritability and trait relevance. **A.** Distributions of distal and local heritability of transcripts across the four tissues. Overall local and distal factors contribute equally to transcript heritability. Arrows indicate the median of each distribution. The relationship between **(B.)** local and **(C.)** distal heritability and trait relevance across all four tissues. Here trait relevance is defined as the maximum correlation between the transcript and all traits. The lower line in each panel shows the mean trait correlation, and the upper line shows the upper 95th percentile of trait correlation in transcripts with increasing variance explained either locally (B) or distally (C). Transcripts high local heritability have lower trait correlations. In contrast, transcripts with large distal heritability also have high correlations with traits.

119 each transcript. The local heritability of transcripts was negatively associated with their trait relevance (Fig.
 120 2B), suggesting that the more local genotype influenced transcript abundance, the less effect this variation
 121 had on the measured traits. Conversely, the distal heritability of transcripts was positively associated with
 122 trait relevance (Fig. 2C). That is, transcripts that were more highly correlated with the measured traits
 123 tended to be distally, rather than locally, heritable. Importantly, this pattern was consistent across all tissues.
 124 This finding is consistent with previous observations that transcripts with low local heritability explain more
 125 expression-mediated disease heritability than transcripts with high local heritability¹⁹. However, the positive
 126 relationship between trait correlation and distal heritability demonstrated further that there are diffuse

127 genetic effects throughout the genome converging on trait-related transcripts.

128 **High-Dimensional Mediation Analysis identified a high-heritability composite trait that was**
129 **mediated by a composite transcript**

130 The above univariate analyses establish the importance of distal heritability for trait-relevant transcripts.
131 However, the number of transcripts dramatically exceeds the number of phenotypes. Thus, we expect the
132 heritable, trait-relevant transcripts to be highly correlated and organized according to coherent, biological
133 processes representing the mediating endophenotypes driving clinical trait variation. To identify these
134 endophenotypes in a theoretically principled way, we developed a novel dimension-reduction technique,
135 high-dimension mediation analysis (HDMA), that uses the theory of causal graphical models to identify a
136 transcriptomic signature that is simultaneously 1) highly heritable, 2) strongly correlated to the measured
137 phenotypes, and 3) conforms to the causal mediation hypothesis (Fig. 3). HDMA projects the high-dimensional
138 genome, transcriptome, and phenotype data onto one-dimensional scores—a composite genome score (G_C), a
139 composite transcriptome score (T_C), and a composite phenotype score (P_C)—and uses the univariate theory of
140 mediation to constrain these projections to satisfy the hypotheses of perfect mediation, namely that upon
141 controlling for the transcriptomic score, the genome score is uncorrelated to the phenotype score. A complete
142 mathematical derivation and implementation details for HDMA are available in Supp. Methods.

143 Using HDMA we identified the major axis of variation in the transcriptome that was consistent with mediating
144 the effects of the genome on metabolic traits (Fig 3). Fig. 3A shows the partial correlations (ρ) between
145 the pairs of these composite vectors. The partial correlation between G_C and T_C was 0.43, and the partial
146 correlation between T_C and P_C was 0.59. However, when the transcriptome was taken into account, the
147 partial correlation between G_C and P_C was effectively zero (0.14). P_C captured 30% of the overall trait
148 variance, and its estimated heritability was 0.71 ± 0.084 , which was higher than any of the measured traits
149 (Fig. 1F). Thus, HDMA identified a maximally heritable metabolic composite trait and a highly heritable
150 component of the transcriptome that are correlated as expected in the perfect mediation model.

151 As discussed in Supp. Methods, HDMA is related to a generalized form of canonical correlation analysis
152 (CCA). Standard CCA is prone to over-fitting because in any two large matrices it can be trivial to identify
153 highly correlated composite vectors³⁵. To assess whether our implementation of HDMA was similarly prone
154 to over-fitting in a high-dimensional space, we performed permutation testing. We permuted the individual
155 labels on the transcriptome matrix 10,000 times and recalculated the path coefficient, which is the correlation
156 of G_C and T_C multiplied by the correlation of T_C and P_C . This represents the strength of the path from
157 G_C to P_C that is putatively mediated through T_C . The null distribution of the path coefficient is shown in

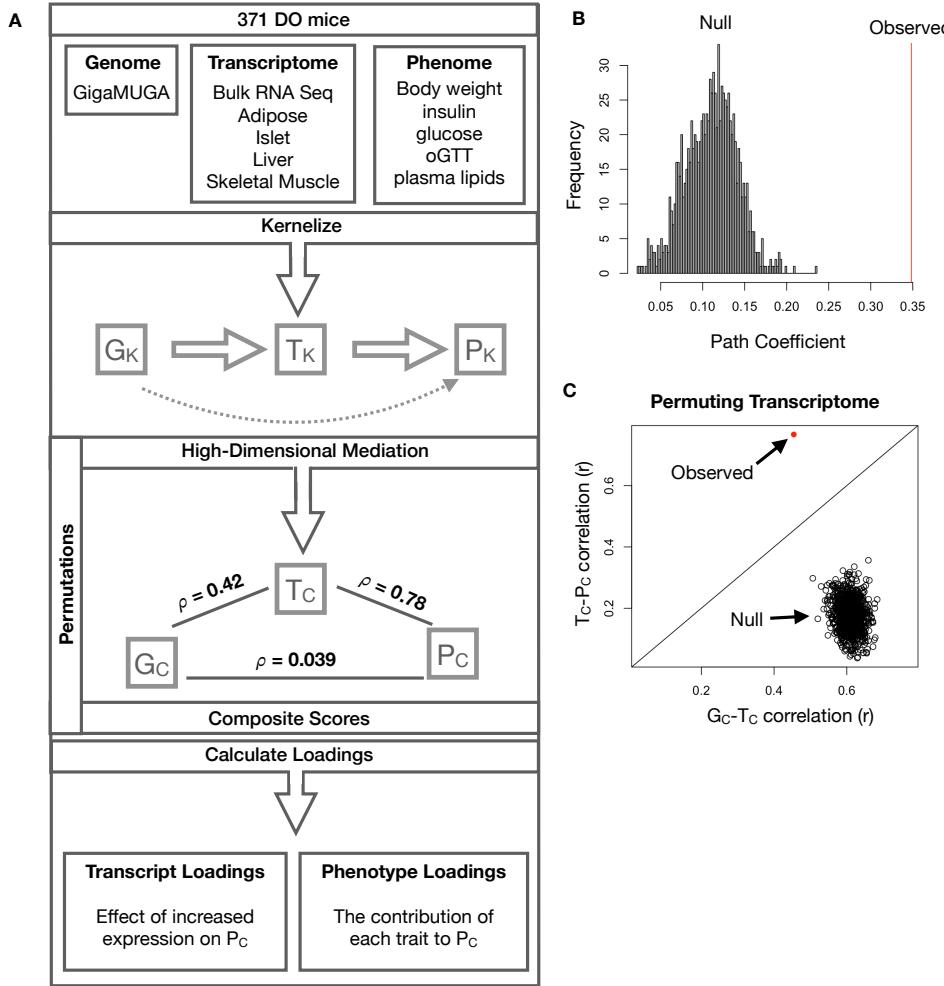


Figure 3: High-dimensional mediation. **A.** Workflow indicating major steps of high-dimensional mediation. The genotype, transcriptome, and phenotype matrices were independently normalized and converted to kernel matrices representing the pairwise relationships between individuals for each data modality (K_G = genome kernel, K_T = transcriptome kernel; K_P = phenome kernel). High-dimensional mediation was applied to these matrices to maximize the direct path $G \rightarrow T \rightarrow P$, the mediating pathway (arrows), while simultaneously minimizing the direct $G \rightarrow P$ pathway (dotted line). The composite vectors that resulted from high-dimensional mediation were G_c , T_c , and P_c . The partial correlations ρ between these vectors indicated perfect mediation. Transcript and trait loadings were calculated as described in the methods. **B.** The null distribution of the path coefficient derived from 10,000 permutations compared to the observed path coefficient (red line). **C.** The null distribution of the G_c-T_c correlation vs. the T_c-P_c correlation compared with the observed value (red dot).

Fig. 3B, and the observed path coefficient from the original data is indicated by a red line. The observed path coefficient was well outside the null distribution generated by permutations ($p < 10^{-16}$). Fig. 3C illustrates this observation in more detail. Although we identified high correlations between G_c and T_c , and modest correlations between T_c and P_c in the null data (Fig 3C), these two values could not be maximized simultaneously in the null data. In contrast, the red dot shows that in the real data both the G_c-T_c

163 correlation and the T_C - P_C correlation could be maximized simultaneously suggesting that the path from
164 genotype to phenotype through transcriptome is highly non-trivial and identifiable in this case. These results
165 suggest that these composite vectors represent genetically determined variation in phenotype that is mediated
166 through genetically determined variation in transcription.

167 **Body weight and insulin resistance were highly represented in the expression-mediated com-**
168 **posite trait**

169 Each composite score is a weighted combination of the measured variables. The magnitude and sign of the
170 weights, called loadings, correspond to the relative importance and directionality of each variable in the
171 composite score. The loadings of each measured trait onto P_C indicate how much each contributed to the
172 composite phenotype. Body weight contributed the most (Fig. 4), followed by homeostatic insulin resistance
173 (HOMA_IR) and fasting plasma insulin levels (Insulin_Fasting). We can thus interpret P_C as an index
174 of metabolic disease (Fig. 4B). Individuals with high values of P_C have a higher metabolic disease index
175 (MDI) and greater metabolic disease, including higher body weight and higher insulin resistance. We refer to
176 P_C as the MDI going forward. Traits contributing the least to the MDI were measures of cholesterol and
177 pancreas composition. Thus, when we interpret the transcriptomic signature identified by HDMA, we are
178 explaining primarily the putative transcriptional mediation of body weight and insulin resistance, as opposed
179 to cholesterol measurements.

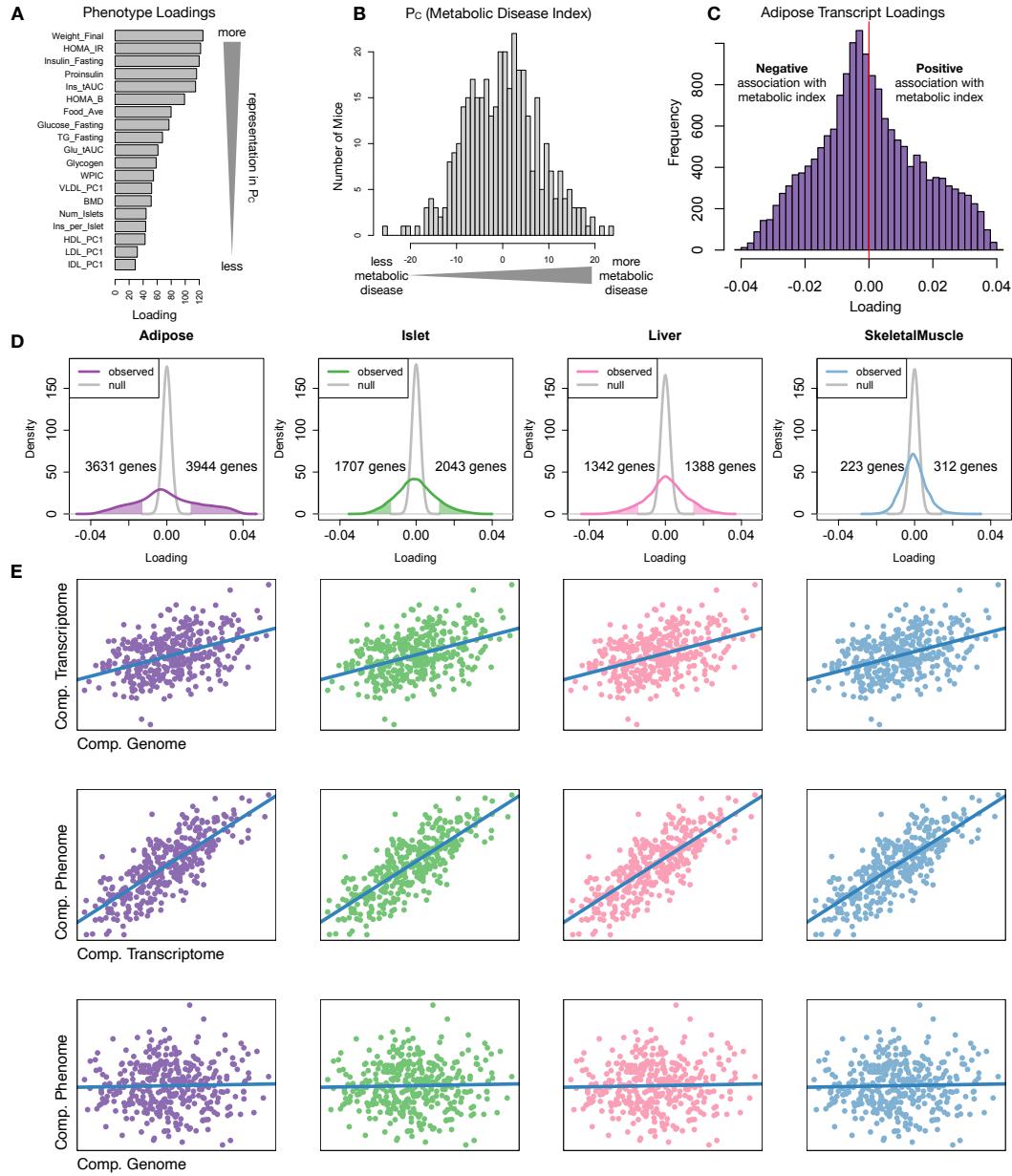


Figure 4: Interpretation of loadings. **A.** Loadings across traits. Body weight and insulin resistance contributed the most to the composite trait. **B.** Phenotype scores across individuals. Individuals with large positive phenotype scores had higher body weight and insulin resistance than average. Individuals with large negative phenotype scores had lower body weight and insulin resistance than average. **C.** Distribution of transcript loadings in adipose tissue. For transcripts with large positive loadings, higher expression was associated with higher phenotype scores. For transcripts with large negative loadings, higher expression was associated with lower phenotype scores. **D.** Distributions of loadings across tissues compared to null distributions. Shaded areas represent loadings that were more extreme than the null distribution. Numbers indicate how many transcripts had loadings above and below the extremes of the null. Transcripts in adipose tissue had the most extreme loadings indicating that transcripts in adipose tissue were the best mediators of the genetic effects on body weight and insulin resistance. **E.** Dot plots showing correlations between the composite genome (G_C), composite transcriptome (T_C), and the composite phenotype (P_C). The G_C and T_C are positively correlated, the G_T and G_P are positively correlated, but the G_C and G_P are uncorrelated.

¹⁸⁰ **High-loading transcripts had low local heritability, high distal heritability, and were linked**
¹⁸¹ **mechanistically to obesity**

¹⁸² We interpreted large loadings onto transcripts as indicating strong mediation of the effect of genetics on the
¹⁸³ MDI. Large positive loadings indicate that higher expression was associated with a higher MDI (i.e. higher
¹⁸⁴ risk of obesity and metabolic disease on the HFHS diet) (Fig. 4C). Conversely, large negative loadings
¹⁸⁵ indicate that high expression of these transcripts was associated with a lower MDI (i.e. lower risk of obesity
¹⁸⁶ and metabolic disease on the HFHS diet) (Fig. 4C). We used gene set enrichment analysis (GSEA)^{36;37} to
¹⁸⁷ look for biological processes and pathways that were enriched at the top and bottom of this list (Methods).

¹⁸⁸ In adipose tissue, both GO processes and KEGG pathway enrichments pointed to an axis of inflammation and
¹⁸⁹ metabolism (Figs. S3 and S4). GO terms and KEGG pathways associated with inflammation were positively
¹⁹⁰ associated with the MDI, indicating that increased expression in inflammatory pathways was associated
¹⁹¹ with a higher burden of disease. It is well established that adipose tissue in obese individuals is inflamed
¹⁹² and infiltrated by macrophages^{38–42}, and the results here suggest that this may be a dominant heritable
¹⁹³ component of metabolic disease.

¹⁹⁴ The strongest negative enrichments in adipose tissue were related to mitochondrial activity in general, and
¹⁹⁵ thermogenesis in particular (Figs. S3 and S3). Genes in the KEGG oxidative phosphorylation pathway were
¹⁹⁶ almost universally negatively loaded in adipose tissue, suggesting that increased expression of these genes was
¹⁹⁷ associated with reduced MDI (Supp. Fig. S5). Consistent with this observation, it has been shown previously
¹⁹⁸ that mouse strains with greater thermogenic potential are also less susceptible to obesity on an obesigenic
¹⁹⁹ diet⁴³.

²⁰⁰ Transcripts associated with the citric acid cycle as well as the catabolism of the branched-chain amino acids
²⁰¹ (valine, leucine, and isoleucine) were strongly enriched with negative loadings in adipose tissue (Supp. Figs.
²⁰² S3, S6 and S7). Expression of genes in both pathways (for which there is some overlap) has been previously
²⁰³ associated with insulin sensitivity^{12;44;45}, suggesting that heritable variation in regulation of these pathways
²⁰⁴ may influence risk of insulin resistance.

²⁰⁵ Looking at the 10 most positively and negatively loaded transcripts from each tissue, it is apparent that
²⁰⁶ transcripts in the adipose tissue had the largest loadings, both positive and negative (Fig. 5A bar plot). This
²⁰⁷ suggests that much of the effect of genetics on body weight and insulin resistance is mediated through gene
²⁰⁸ expression in adipose tissue. This finding does not speak to the relative importance of tissues not included
²⁰⁹ in this study, such as brain, in which transcriptional variation may mediate a large portion of the genetic
²¹⁰ effect on obesity. The strongest loadings in liver and pancreas were comparable, and those in skeletal muscle

were the weakest (Fig. 5A), suggesting that less of the genetic effects were mediated through transcription in skeletal muscle. As expected, heritability analysis showed that transcripts with the largest loadings had higher distal heritability than local heritability (Fig. 5A heat map and box plot). This pattern contrasts with transcripts nominated by TWAS (Fig. 5B), which tended to have lower loadings, higher local heritability and lower distal heritability. Transcripts with the highest local heritability in each tissue (Fig. 5C) had the lowest loadings, consistent with our findings above (Fig. 2B).

We performed a literature search for the genes in each of these groups along with the terms “diabetes”, “obesity”, and the name of the expressing tissue to determine whether any of these genes had previous associations with metabolic disease in the literature (Methods). Multiple genes in each group had been previously associated with obesity and diabetes (Fig. 5 bolded gene names). Genes with high loadings were most highly enriched for previous literature support. They were 2.1 times more likely than TWAS hits and 3.8 times more likely than genes with high local heritability to be previously associated with obesity or diabetes.

Tissue-specific transcriptional programs were associated with metabolic traits

Clustering of transcripts with top loadings in each tissue showed tissue-specific functional modules associated with obesity and insulin resistance (Fig. 6A) (Methods). The clustering highlights the importance of immune activation particularly in adipose tissue. The “mitosis” cluster had large positive loadings in three of the four tissues potentially suggesting system-wide proliferation of immune cells. Otherwise, all clusters were strongly loaded in only one or two tissues. For example, the lipid metabolism cluster was loaded most heavily in liver. The positive loadings suggest that high expression of these genes, particularly in the liver, was associated with increased metabolic disease. This cluster included the gene *Pparg*, whose primary role is in the adipose tissue where it is considered a master regulator of adipogenesis⁴⁶. Agonists of *Pparg*, such as thiazolidinediones, are FDA-approved to treat type II diabetes, and reduce inflammation and adipose hypertrophy⁴⁶. Consistent with this role, the loading for *Pparg* in adipose tissue was negative, suggesting that higher expression was associated with leaner mice (Fig. 6B). In contrast, *Pparg* had a large positive loading in liver, where it is known to play a role in the development of hepatic steatosis, or fatty liver. Mice that lack *Pparg* specifically in the liver, are protected from developing steatosis and show reduced expression of lipogenic genes^{47;48}. Overexpression of *Pparg* in the livers of mice with a *Ppara* knockout, causes upregulation of genes involved in adipogenesis⁴⁹. In the livers of both mice and humans high *Pparg* expression is associated with hepatocytes that accumulate large lipid droplets and have gene expression profiles similar to that of adipocytes^{50;51}. The local and distal heritability of *Pparg* is low in adipose tissue suggesting its expression in this tissue is highly constrained in the population (Fig. 6B). However, the distal heritability of *Pparg* in liver is relatively

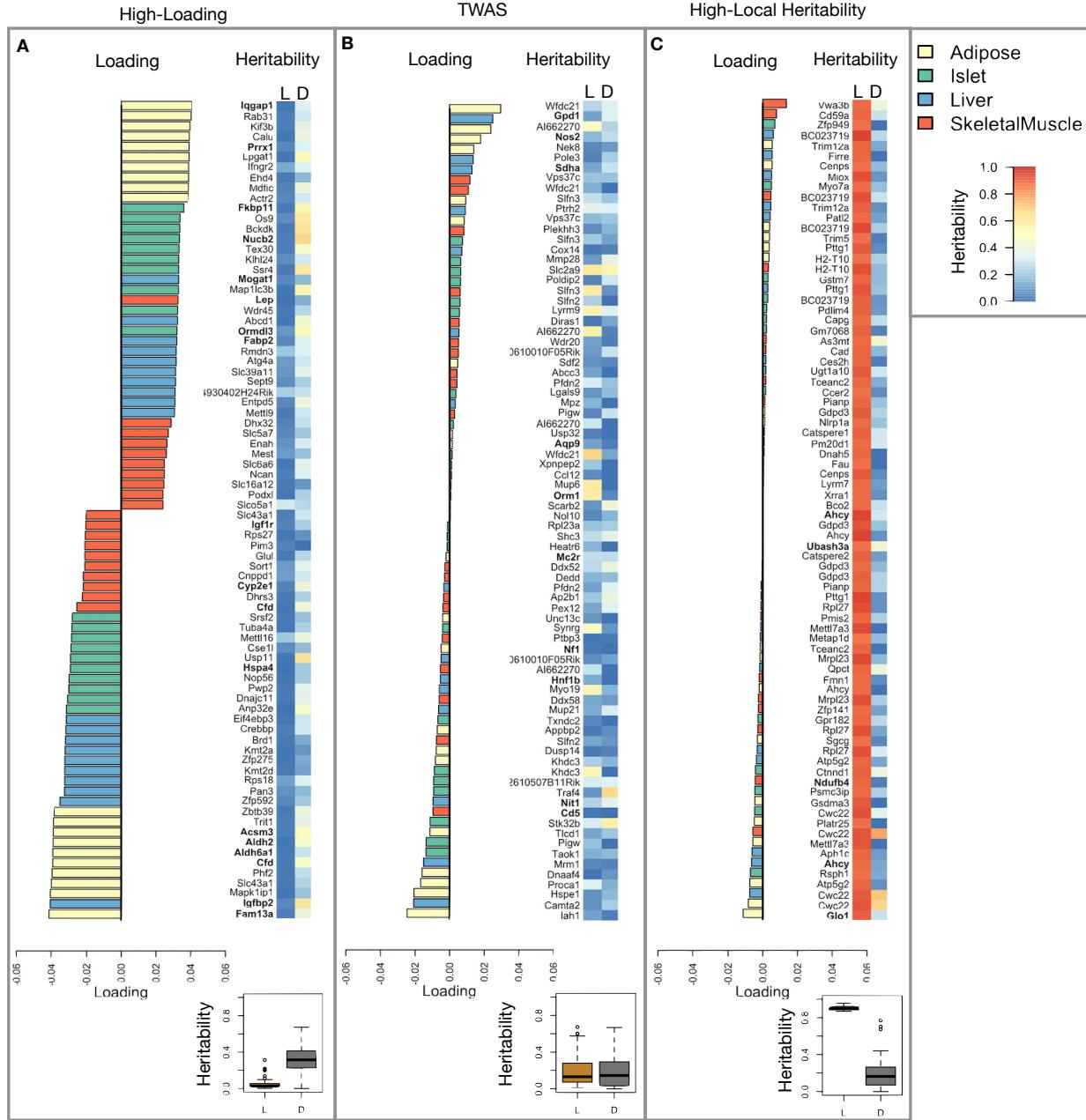


Figure 5: Transcripts with high loadings have high distal heritability and literature support. Each panel has a bar plot showing the loadings of transcripts selected by different criteria. Bar color indicates the tissue of origin. The heat map shows the local (L - left) and distal (D - right) heritability of each transcript.

A. Loadings for the 10 transcripts with the largest positive loadings and the 10 transcripts with the largest negative loadings for each tissue.

B. Loadings of TWAS candidates with the 10 largest positive correlations with traits and the largest negative correlations with traits across all four tissues.

C. The transcripts with the largest local heritability (top 20) across all four tissues.

242 high suggesting it is complexly regulated and has sufficient variation in this

245 the importance of tissue context when investigating the role of heritable transcript variability in driving
 246 phenotype.

247 Gene lists for all clusters are available in Supp. File 1.

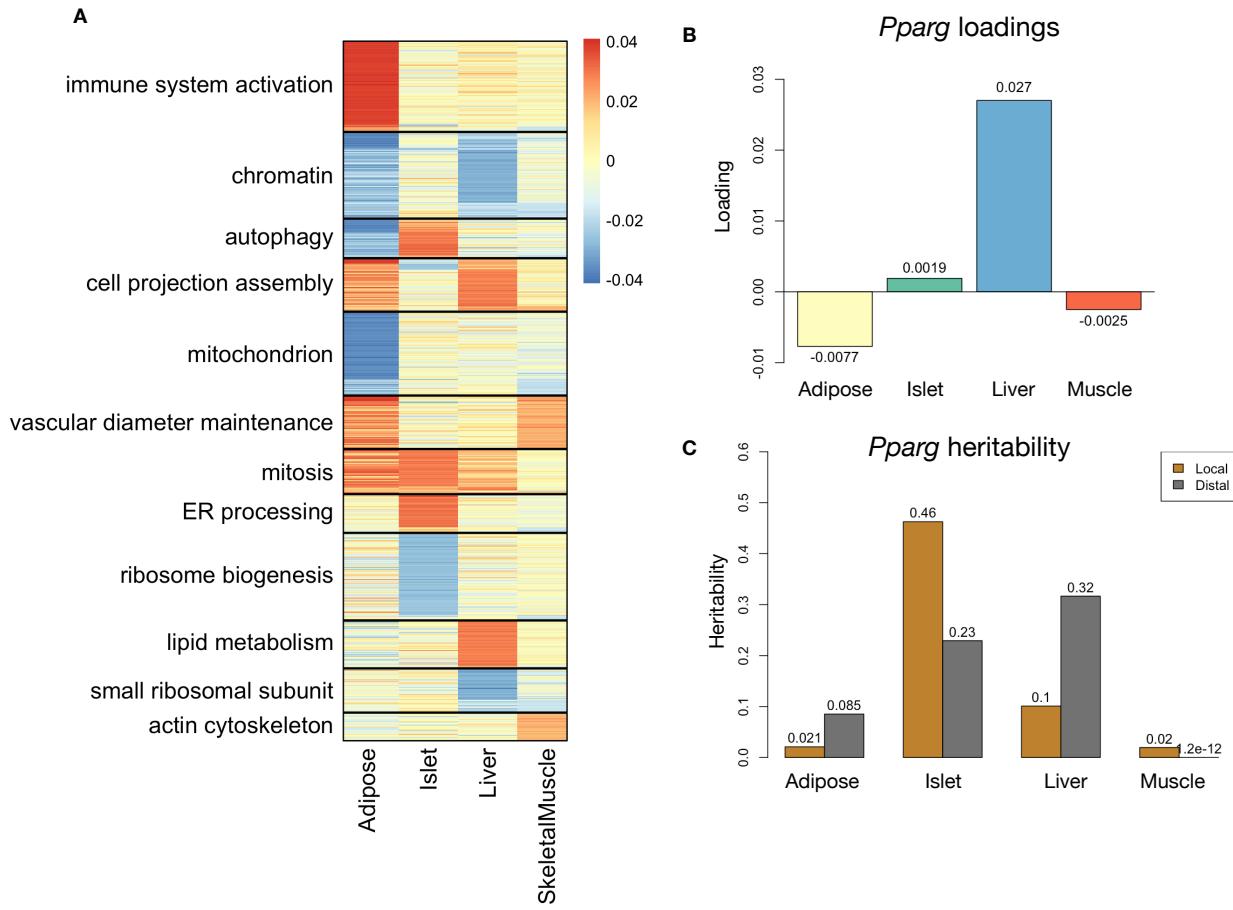


Figure 6: Tissue-specific transcriptional programs were associated with obesity and insulin resistance. **A** Heat map showing the loadings of all transcripts with loadings greater than 2.5 standard deviations from the mean in any tissue. The heat map was clustered using k medoid clustering. Functional enrichments of each cluster are indicated along the left margin. **B** Loadings for *Pparg* in different tissues. **C** Local and distal of *Pparg* expression in different tissues.

248 **Gene expression, but not local eQTLs, predicted body weight in an independent population**

249 To test whether the transcript loadings identified in the DO could be translated to another population, we
 250 tested whether they could predict metabolic phenotype in an independent population of CC-RIX mice, which
 251 were F1 mice derived from multiple pairings of Collaborative Cross (CC)^{52;32;53;54} strains (Fig. 7) (Methods).
 252 We tested two questions. First, we asked whether the loadings identified in the DO mice were relevant to
 253 the relationship between the transcriptome and the phenotype in the CC-RIX. We predicted body weight
 254 (a surrogate for MDI) in each CC-RIX individual using measured gene expression in each tissue and the

transcript loadings identified in the DO (Methods). The predicted body weight and acutal body weight were highly correlated (Fig. 7B left column). The best prediction was achieved for adipose tissue, which supports the observation in the DO that adipose expression was the strongest mediator of the genetic effect on MDI. This result also confirms the validity and translatability of the transcript loadings and their relationship to metabolic disease.

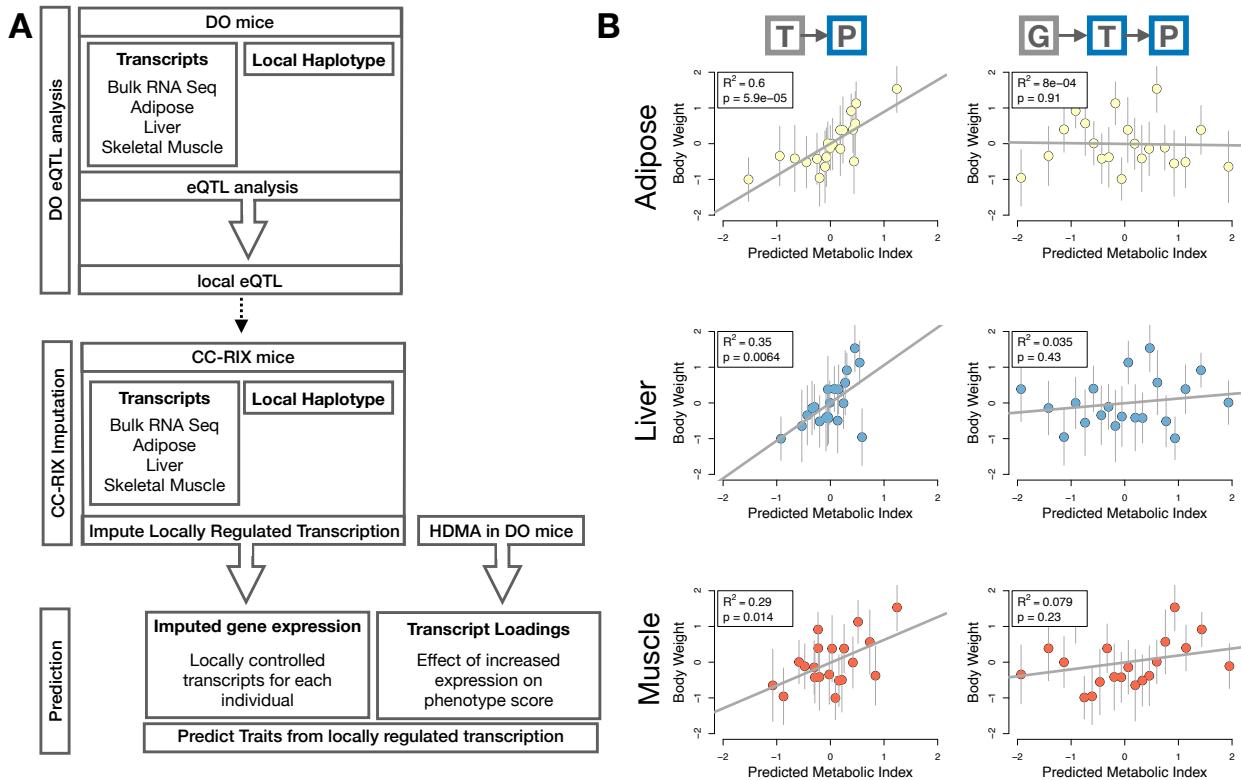


Figure 7: Transcription, but not local genotype, predicts phenotype in the CC-RIX. **A.** Workflow showing procedure for translating HDMA results to an independent population of mice. **B.** Relationships between the predicted metabolic disease index (MDI) and measured body weight. The left column shows the predictions using measured transcripts. The right column shows the prediction using transcript levels imputed from local genotype. Gray boxes indicate measured quantities, and blue boxes indicate calculated quantities. The dots in each panel represent individual CC-RIX strains. The gray lines show the standard deviation on body weight for the strain.

The second question related to the source of the relevant variation in gene expression. If local regulation was the predominant factor influencing trait-relevant gene expression, we should be able to predict phenotype in the CC-RIX using transcripts imputed from local genotype (Fig. 7A). The DO and the CC-RIX were derived from the same eight founder strains and so carry the same alleles throughout the genome. We imputed gene expression in the CC-RIX using local genotype and were able to estimate variation in gene transcription robustly (Supp. Fig. S8). However, these imputed values failed to predict body weight in the CC-RIX when weighted with the loadings from HDMA. (Fig. 7B right column). This result suggests that local regulation of

267 gene expression is not the primary factor driving heritability of complex traits. It is also consistent with our
268 findings in the DO population that distal heritability was a major driver of trait-relevant gene expression and
269 that high-loading transcripts had comparatively high distal and low local heritability.

270 **Distally heritable transcriptomic signatures reflected variation in composition of adipose tissue
271 and islets**

272 The interpretation of global genetic influences on gene expression and phenotype is potentially more challenging
273 than the interpretation and translation of local genetic influences, as genetic effects cannot be localized to
274 individual gene variants or transcripts. However, there are global patterns across the loadings that can
275 inform mechanism. For example, heritable variation in cell type composition can be inferred from transcript
276 loadings. We observed above that immune activation in the adipose tissue was a highly enriched process
277 correlating with obesity in the DO population. In humans, it has been extensively observed that macrophage
278 infiltration in adipose tissue is a marker of obesity and metabolic disease⁵⁵. To determine whether the
279 immune activation reflected a heritable change in cell composition in adipose tissue in DO mice, we compared
280 loadings of cell-type specific genes in adipose tissue (Methods). The mean loading of macrophage-specific
281 genes was significantly greater than 0 (Fig. 8A), indicating that obese mice were genetically predisposed
282 to have high levels of macrophage infiltration in adipose tissue in response to the HFHS diet. Loadings for
283 marker genes for other cell types were not statistically different from zero, indicating that changes in the
284 abundance of those cell types is not a mediator of MDI.

285 We also compared loadings of cell-type specific transcripts in islet (Methods). The mean loadings for alpha-cell
286 specific transcripts were significantly greater than 0, while the mean loadings for delta- and endothelial-cell
287 specific genes were significantly less than 0 (Fig. 8B). These results suggest that mice with higher MDI
288 inherited an altered cell composition that predisposed them to metabolic disease, or that these compositional
289 changes were induced by the HFHS diet in a heritable way. In either case, these results support the hypothesis
290 that alterations in islet composition drive variation in MDI. Notably, the mean loading for pancreatic beta cell
291 marker transcripts was not significantly different from zero. We stress that this is not necessarily reflective of
292 the function of the beta cells in the obese mice, but rather suggests that any variation in the number of beta
293 cells in these mice was unrelated to obesity and insulin resistance, the major contributors to MDI. This is
294 further consistent with the islet composition traits having small loadings in the phenome score (Fig. 4).

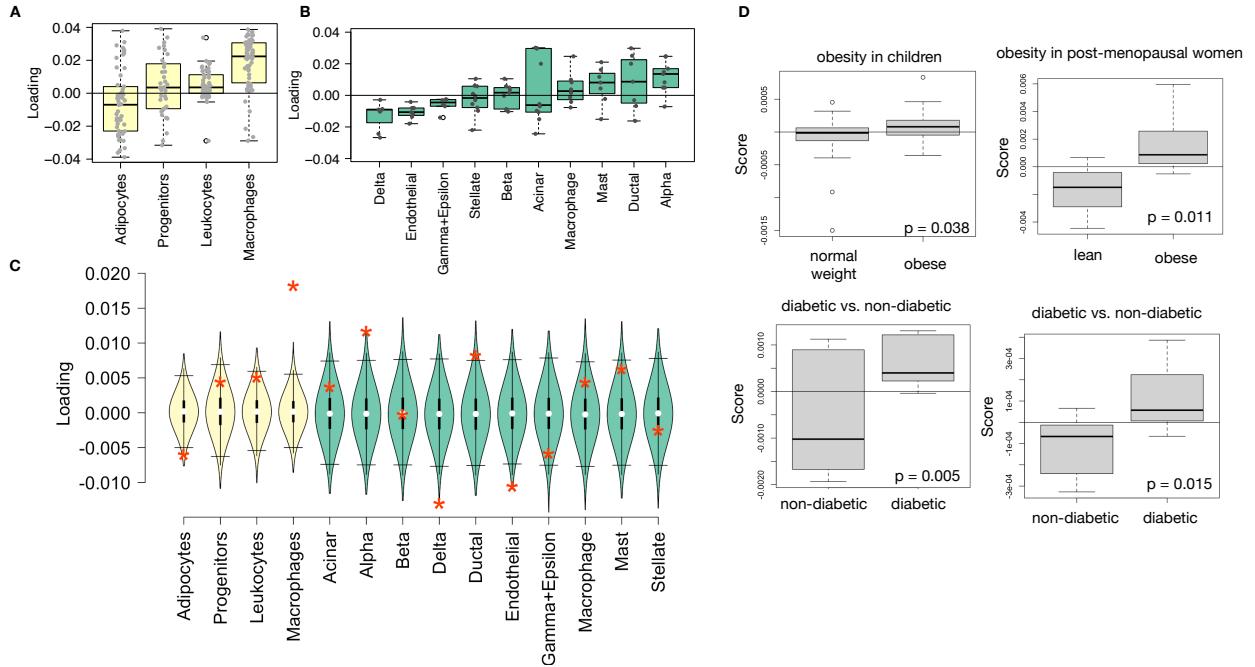


Figure 8: HDMA results translate to humans. **A.** Distribution of loadings for cell-type-specific transcripts in adipose tissue. **B.** Distribution of loadings for cell-type-specific transcripts in pancreatic islets (green). **C.** Null distributions for the mean loading of randomly selected transcripts in each cell type compared with the observed mean loading of each group of transcripts (red asterisk). **D.** Predictions of metabolic phenotypes in four adipose transcription data sets downloaded from GEO. In each study the obese/diabetic patients were predicted to have greater metabolic disease than the lean/non-diabetic patients based on the HDMA results from DO mice.

295 Heritable transcriptomic signatures translated to human disease

296 Ultimately, the heritable transcriptomic signatures that we identified in DO mice will be useful if they inform
 297 mechanism and treatment of human disease. To investigate the potential for translation of the gene signatures
 298 identified in DO mice, we compared them to transcriptional profiles in obese and non-obese human subjects
 299 (Methods). We limited our analysis to adipose tissue because the adipose tissue signature had the strongest
 300 relationship to obesity and insulin resistance in the DO.

301 We calculated a predicted MDI for each individual in the human studies based on their adipose tissue gene
 302 expression (Methods) and compared the predicted scores for obese and non-obese groups as well as diabetic
 303 and non-diabetic groups. In all cases, the predicted MDIs were higher on average for individuals in the
 304 obese and diabetic groups compared with the lean and non-diabetic groups (Fig. 8D). This indicates that
 305 the distally heritable signature of MDI identified in DO mice is relevant to obesity and diabetes in human
 306 subjects.

307 **Existing therapies are predicted to target mediator gene signatures**

308 Another application of the transcript loading landscape is in ranking potential drug candidates for the
309 treatment of metabolic disease. Although high-loading transcripts may be good candidates for understanding
310 specific biology related to obesity, the transcriptome overall is highly interconnected and redundant. The
311 ConnectivityMap (CMAP) database⁵⁶ developed by the Broad Institute allows querying thousands of
312 compounds that reverse or enhance the extreme ends of transcriptomic signatures in multiple different cell
313 types. By identifying drugs that reverse pathogenic transcriptomic signatures, we can potentially identify
314 compounds that have favorable effects on gene expression. To test this hypothesis, we queried the CMAP
315 database through the CLUE online query tool (<https://clue.io/query/>, version 1.1.1.43) (Methods). We
316 identified top anti-correlated hits across all cell types (Supp. Figs S9 and S10). To get more tissue-specific
317 results, we also looked at top results in cell types that most closely resembled our tissues. We looked at
318 results in adipocytes (ASC) as well as pancreatic tumor cells (YAPC) regardless of *p* value (Supp. Figs S11
319 and S12).

320 Looking across all cell types, the notable top hits from the adipose tissue loadings included mTOR inhibitors
321 and glucocorticoid agonists (Supp. Fig. S9). It is thought that metformin, which is commonly used to
322 improve glycemic control, acts, at least in part, by inhibiting mTOR signaling^{57;58}. However, long-term use
323 of other mTOR inhibitors, such as rapamycin, are known to cause insulin resistance and β -cell toxicity^{58–60}.
324 Glucocorticoids are used to reduce inflammation, which was a prominent signature in the adipose tissue,
325 but these drugs also promote hyperglycemia and diabetes^{61;62}. Acute treatment with glucocorticoids has
326 further been shown to reduce thermogenesis in rodent adipocytes^{63–65}, but increase thermogenesis in human
327 adipocytes^{66;67}. Thus, the pathways identified by CMAP across all cell types were highly related to the
328 transcript loading profiles, but the relationship was not a simple reversal.

329 The top hit for the adipose composite transcript in CMAP adipocytes was a PARP inhibitor (Supp. Fig.
330 S11). PARPs play a role in lipid metabolism and are involved in the development of obesity and diabetes⁶⁸.
331 PARP1 inhibition increases mitochondrial biogenesis⁶⁹. Inhibition of PARP1 activity can further prevent
332 necrosis in favor of the less inflammatory apoptosis⁷⁰, thereby potentially reducing inflammation in stressed
333 adipocytes. Other notable hits among the top 20 were BTK inhibitors, which have been observed to suppress
334 inflammation and improve insulin resistance⁷¹ as well as to reduce insulin antibodies in type I diabetes⁷².
335 IkappaB kinase (IKK) is an enzyme complex involved in regulating cellular responses to inflammation⁷³.
336 Inhibitors of IKK have been shown to improve glucose control in type II diabetes^{74;75}.

337 Among the top most significant hits for the transcript loadings from pancreatic islets (Supp. Fig. S10),

338 was suppression of T cell receptor signaling, which is known to be involved in Type 1 diabetes⁷⁶, as well as
339 TNFR1, which has been associated with mortality in diabetes patients⁷⁷. Suppression of NOD1/2 signaling
340 was also among the top hits. NOD1 and 2 sense ER stress^{78;79}, which is associated with β -cell death in type
341 1 and type 2 diabetes⁸⁰. This cell death process is dependent on NOD1/2 signaling⁷⁸, although the specifics
342 have not yet been worked out.

343 We also looked specifically at hits in pancreatic tumor cells (YAPC) regardless of significance level to get a
344 transcriptional response more specific to the pancreas (Supp. Fig. S12). Hits in this list included widely used
345 diabetes drugs, such as sulfonylureas, PPAR receptor agonists, and insulin sensitizers. Rosiglitazone is a
346 PPAR- γ agonist and was one of the most prescribed drugs for type 2 diabetes before its use was reduced due
347 to cardiac side-effects⁸¹. Sulfonylureas are another commonly prescribed drug class for type 2 diabetes, but
348 also have notable side effects including hypoglycemia and accelerated β -cell death⁸².

349 In summary, the high-loading transcripts derived from HDMA in mice prioritized of drugs with demonstrated
350 effectiveness in reducing type 2 diabetes phenotypes in humans in a tissue-specific manner. Drugs identified
351 using the islet loadings are known diabetes drugs that act directly on pancreatic function. Drugs identified
352 by the adipose loadings tended to reduce inflammatory responses and have been shown incidentally to reduce
353 obesity-related morbidity.

354 Discussion

355 Here we investigated the relative contributions of local and distal gene regulation in four tissues to heritable
356 variation in traits related to metabolic disease in genetically diverse mice. We found that distal heritability
357 was positively correlated with trait relatedness, whereas high heritability was negatively correlated with
358 trait relatedness. We used a novel high-dimensional mediation analysis (HDMA) to identify tissue-specific
359 composite transcripts that are predicted to mediate the effect of genetic background on metabolic traits. The
360 adipose-derived composite transcript robustly predicted body weight in an independent cohort of diverse
361 mice with disparate population structure, as well as to humans. However, gene expression imputed from
362 local genotype failed to predict body weight in the second population. Taken together, these results highlight
363 the complexity of gene expression regulation in relation to trait heritability and suggest that heritable trait
364 variation is mediated primarily through distal gene regulation.

365 Our result that distal regulation accounted for most trait-related gene expression differences is consistent
366 with a complex model of genetic trait determination. It has frequently been assumed that gene regulation in
367 *cis* is the primary driver of genetically associated trait variation, but attempts to use local gene regulation

368 to explain phenotypic variation have had limited success^{16;17}. In recent years, evidence has mounted that
369 distal gene regulation may be an important mediator of trait heritability^{19;18;83;84}. It has been observed
370 that transcripts with high local heritability explain less expression-mediated disease heritability than those
371 with low local heritability¹⁹. Consistent with this observation, genes located near GWAS hits tend to be
372 complexly regulated¹⁸. They also tend to be enriched with functional annotations, in contrast to genes with
373 simple local regulation, which tend to be depleted of functional annotations suggesting they are less likely
374 to be directly involved in disease traits¹⁸. These observations are consistent with principles of robustness
375 in complex systems in which simple regulation of important elements leads to fragility of the system⁸⁵⁻⁸⁷.
376 Our results are consistent, instead, with a more complex picture where genes whose expression can drive
377 trait variation are buffered from local genetic variation but are extensively influenced indirectly by genetic
378 variation in the regulatory networks converging on those genes.

379 Our results are also consistent with the recently proposed omnigenic model, which posits that complex traits
380 are massively polygenic and that their heritability is spread out across the genome⁸⁸. In the omnigenic model,
381 genes are classified either as “core genes,” which directly impinge on the trait, or “peripheral genes,” which
382 are not directly trait-related, but influence core genes through the complex gene regulatory network. HDMA
383 explicitly models a central proposal of the omnigenic model which posits that once the expression of the
384 core genes (i.e. trait-mediating genes) is accounted for, there should be no residual correlation between the
385 genome and the phenotype. Here, we were able to fit this model and identified a composite transcript that,
386 when taken into account, left no residual correlation between the composite genome and composite phenotype
387 scores (Fig. 3A).

388 Unlike in the omnigenic model, we did not observe a clear demarcation between the core and peripheral
389 genes in loading magnitude, but we do not necessarily expect a clear separation given the complexity of gene
390 regulation and the genotype-phenotype map⁸⁹.

391 An extension of the omnigenic model proposed that most heritability of complex traits is driven by weak
392 distal eQTLs that are potentially below the detection threshold in studies with feasible sample sizes⁸³. This
393 is consistent with what we observed here. For example, *Nucb2*, had a high loading in islets and was also
394 strongly distally regulated (66% distal heritability) (Fig. 5). This gene is expressed in pancreatic β cells and
395 is involved in insulin and glucagon release⁹⁰⁻⁹². Although its transcription was highly heritable in islets, that
396 regulation was distributed across the genome, with no clear distal eQTL (Supp. Fig. S13). Thus, although
397 distal regulation of some genes may be strong, this regulation is likely to be highly complex and not easily
398 localized.

399 Individual high-loading transcripts also demonstrated biologically interpretable, tissue-specific patterns. We
400 highlighted *Pparg*, which is known to be protective in adipose tissue⁴⁶ where it was negatively loaded, and
401 harmful in the liver^{47–51}, where it was positively loaded. Such granular patterns may be useful in generating
402 hypotheses for further testing, and prioritizing genes as therapeutic targets. The tissue-specific nature of
403 the loadings also may provide clues to tissue-specific effects, or side effects, of targeting particular genes
404 system-wide.

405 In addition to identifying individual transcripts of interest, the composite transcripts can be used as weighted
406 vectors in multiple types of analysis, such as drug prioritization using gene set enrichment analysis (GSEA)
407 and the CMAP database. In particular, the CMAP analysis identified drugs which have been demonstrated
408 to reverse insulin resistance and other aspects of metabolic disease. This finding supports the causal role of
409 these full gene signatures in pathogenesis of metabolic disease and thus their utility in prioritizing drugs and
410 gene targets as therapeutics.

411 Together, our results have shown that both tissue specificity and distal gene regulation are critically important
412 to understanding the genetic architecture of complex traits. We identified important genes and gene signatures
413 that were heritable, plausibly causal of disease, and translatable to other mouse populations and to humans.
414 Finally, we have shown that by directly acknowledging the complexity of both gene regulation and the
415 genotype-to-phenotype map, we can gain a new perspective on disease pathogenesis and develop actionable
416 hypotheses about pathogenic mechanisms and potential treatments.

417 Data and Code Availability

418 **DO mice:** Genotypes, phenotypes, and pancreatic islet gene expression data were previously published¹².
419 Gene expression for the other tissues can be found at the Gene Expression Omnibus <https://www.ncbi.nlm.nih.gov/geo/> with the following accession numbers: DO adipose tissue - GSE266549; DO liver tissue
420 - GSE266569; DO skeletal muscle - GSE266567. Expression data with calculated eQTLs are available at
421 Figshare https://figshare.com/articles/dataset/Data_and_code_for_High-Dimensional_Mediation_Analysis_HDMA_in_diversity_outbred_mice/27066979 DOI: 10.6084/m9.figshare.27066979
422
423 10.6084/m9.figshare.27066979.v1

424
425 **CC-RIX mice:** Gene expression can be found at the Gene Expression Omnibus <https://www.ncbi.nlm.nih.gov/geo/> with the following accession numbers: CC-RIX adipose tissue - GSE237737; CC-RIX liver tissue -
426 GSE237743; CC-RIX skeletal muscle - GSE237747. Count matrices and phenotype data can be found at
427 Figshare https://figshare.com/articles/dataset/Data_and_code_for_High-Dimensional_Mediation_Anal

429 ysis_HDMA_in_diversity_outbred_mice/27066979 DOI: 10.6084/m9.figshare.27066979

430 **Code:** All code used to run the analyses reported here are available at Figshare: https://figshare.com/articles/dataset/Data_and_code_for_High-Dimensional_Mediation_Analysis_HDMA_in_diversity_outbred_mice/27066979 DOI: 10.6084/m9.figshare.27066979

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440 sequencing, necropsy services for the tissue harvests, and the Center for Biometric Analysis for metabolic
441 phenotyping.

442 Supplemental Figures

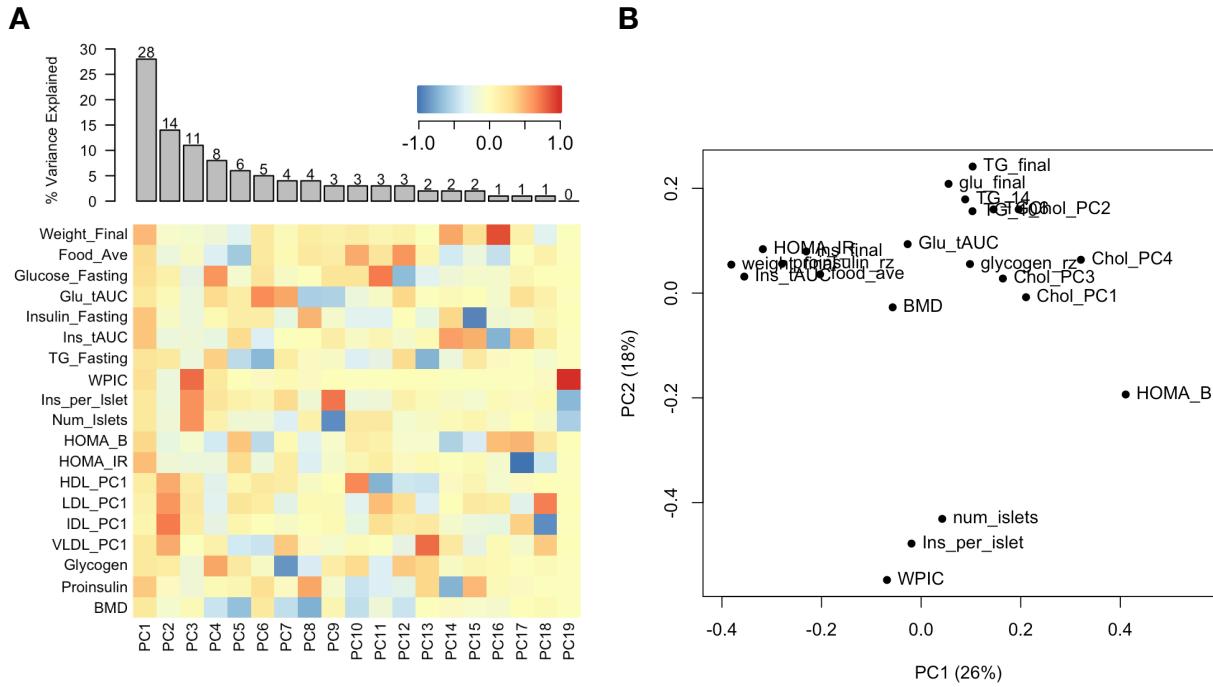


Figure S1: Trait matrix decomposition. **A** The heat map shows the loadings of each trait onto each principal component of the trait matrix. The bars at the top show the percent variance explained for each principal component. **B** Traits plotted by the first and second principal components of the trait matrix. This view shows clustering of traits into insulin- and weight-related traits, lipid-related traits, and ex-vivo pancreatic measurements.

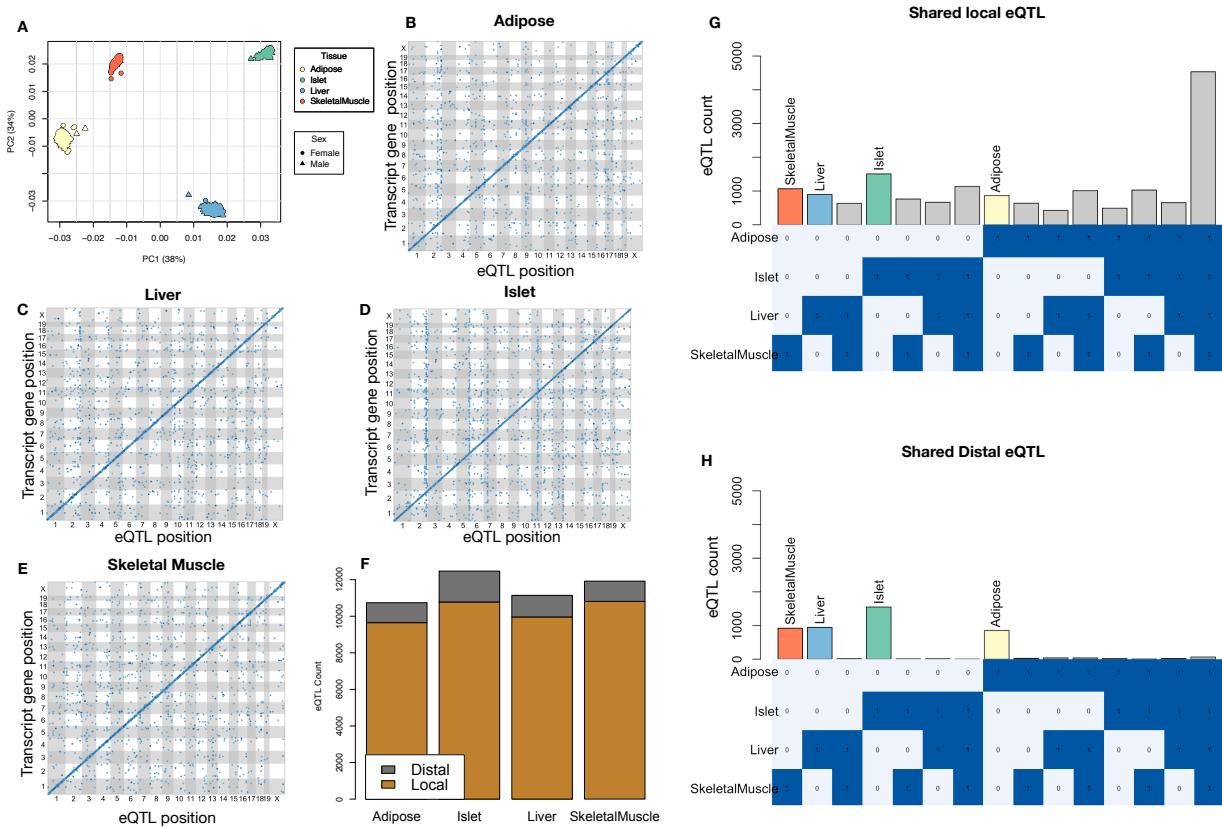


Figure S2: Overview of eQTL analysis in DO mice. **A.** RNA seq samples from the four different tissues clustered by tissue. **B.-E.** eQTL maps are shown for each tissue. The *x*-axis shows the position of the mapped eQTL, and the *y*-axis shows the physical position of the gene encoding each mapped transcript. Each dot represents an eQTL with a minimum LOD score of 8. The dots on the diagonal are locally regulated eQTL for which the mapped eQTL is at the within 4Mb of the encoding gene. Dots off the diagonal are distally regulated eQTL for which the mapped eQTL is distant from the gene encoding the transcript. **F.** Comparison of the total number of local and distal eQTL with a minimum LOD score of 8 in each tissue. All tissues have comparable numbers of eQTL. Local eQTLs are much more numerous than distal eQTL. **G.** Counts of transcripts with local eQTL shared across multiple tissues. The majority of local eQTLs were shared across all four tissues. **H.** Counts of transcripts with distal eQTL shared across multiple tissues. The majority of distal eQTL were tissue-specific and not shared across multiple tissues. For both G and H, eQTL for a given transcript were considered shared in two tissues if they were within 4Mb of each other. Colored bars indicate the counts for individual tissues for easy of visualization.

KEGG pathway enrichments by GSEA

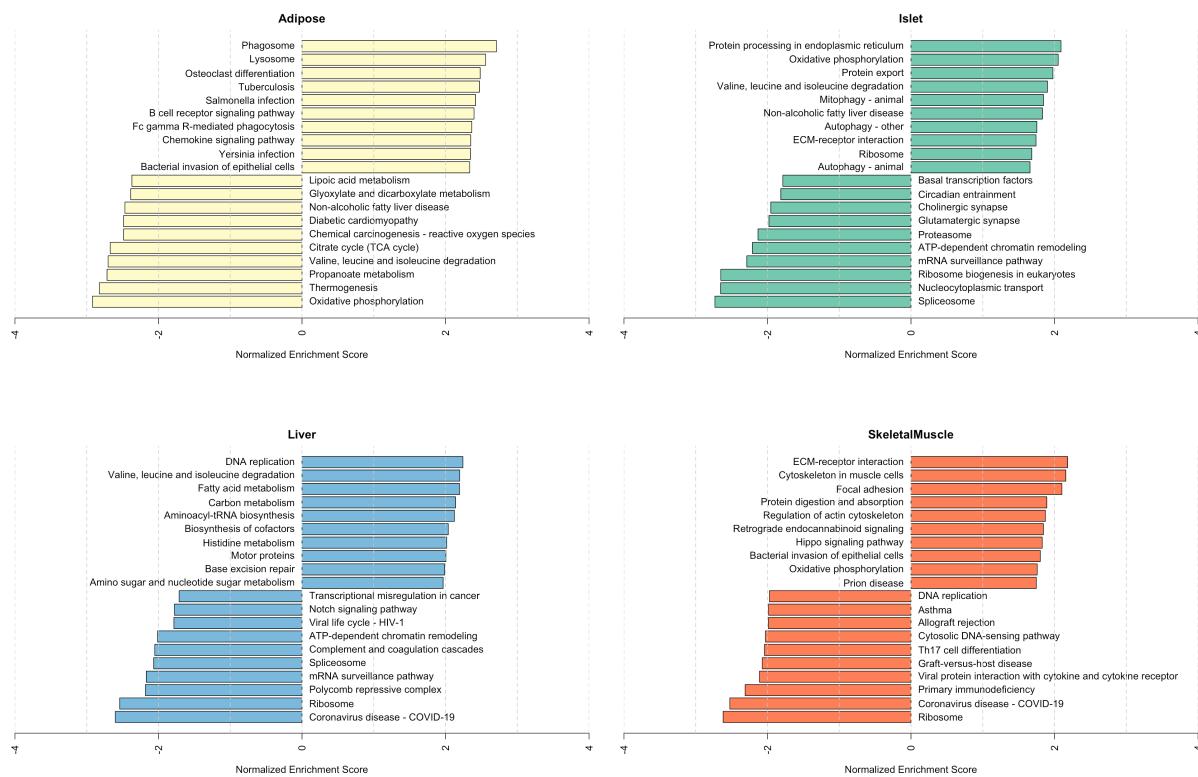


Figure S3: Bar plots showing normalized enrichment scores (NES) for KEGG pathways as determined by fast gene score enrichment analysis (fgsea). Only the top 10 positive and top 10 negative scores are shown. Colors indicate tissue. The name beside each bar shows the name of each enriched KEGG pathway.

Top GO term enrichments by GSEA

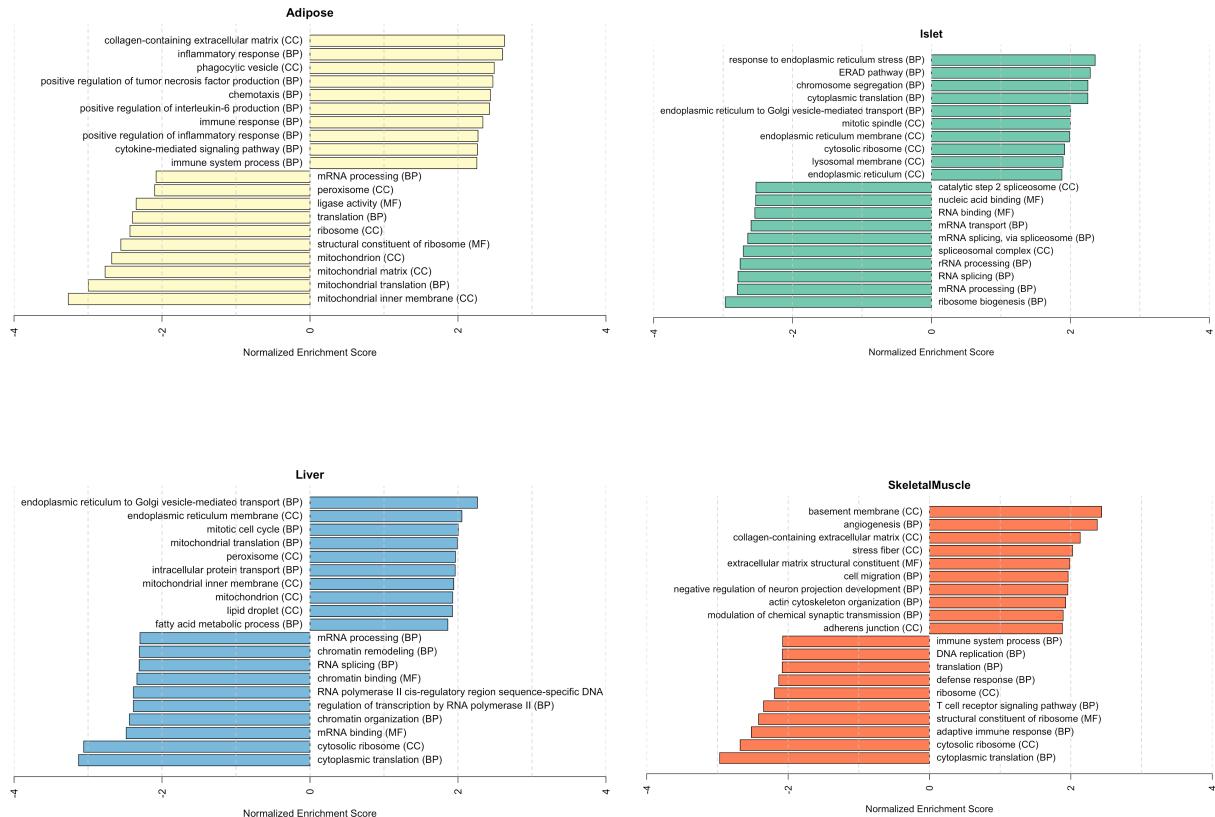


Figure S4: Bar plots showing normalized enrichment scores (NES) for GO terms as determined by fast gene score enrichment analysis (fgsea). Only the top 10 positive and top 10 negative scores are shown. Colors indicate tissue. The name beside each bar shows the name of each enriched GO term. The letters in parentheses indicate whether the term is from the biological process ontology (BP), the molecular function ontology (MF), or the cellular compartment ontology (CC).

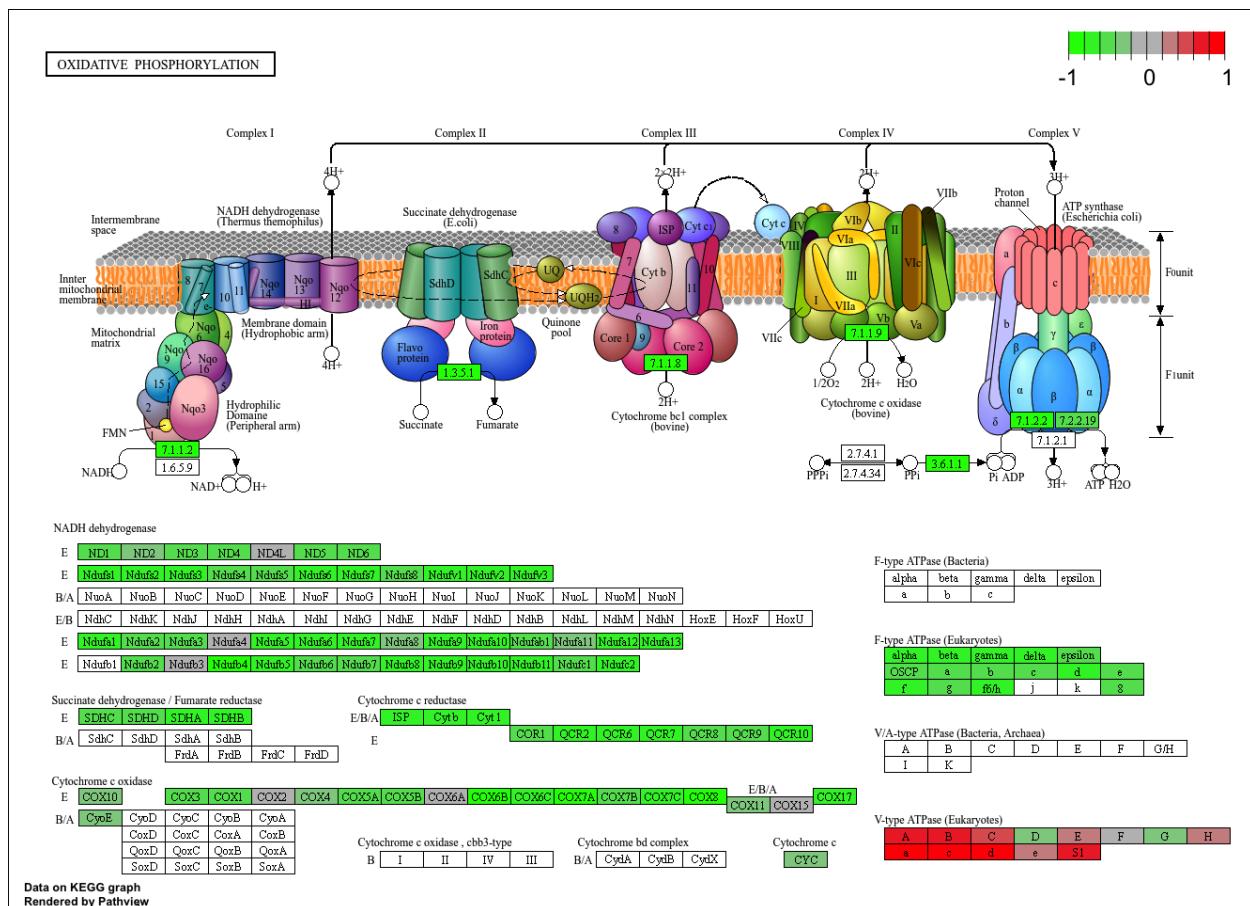


Figure S5: The KEGG pathway for oxidative phosphorylation in mice. Each element is colored based on its HDMA loading from adipose tissue normalized to run from -1 to 1. Genes highlighted in green had negative loadings, and those highlighted in red had positive loadings. Almost the entire pathway was strongly negatively loaded indicating that increased expression of genes involved in oxidative phosphorylation was associated with reduced MDI.

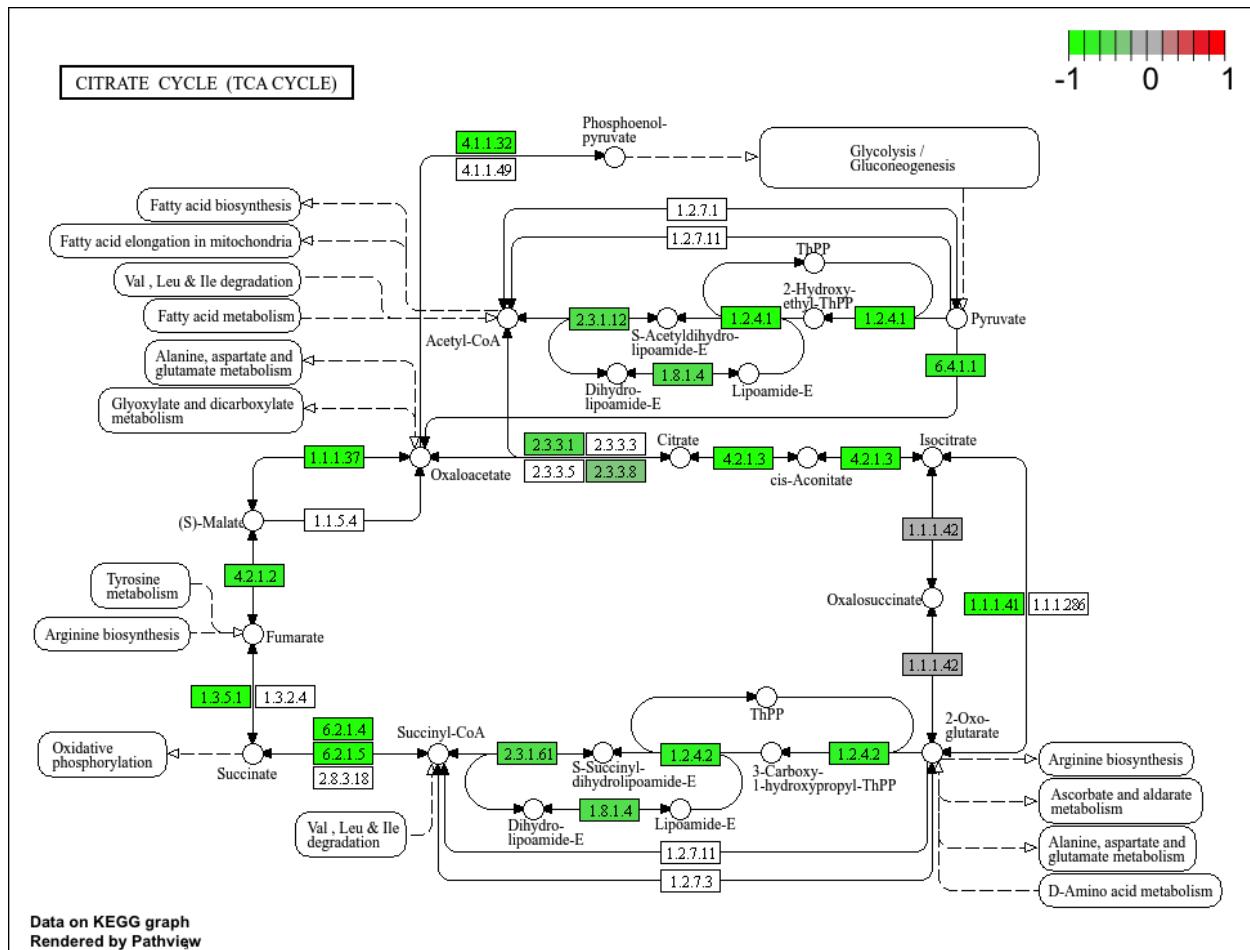


Figure S6: The KEGG pathway for the TCA (citric acid) cycle in mice. Each element is colored based on its HDMA loading from adipose tissue normalized to run from -1 to 1. Genes highlighted in green had negative loadings, and those highlighted in red had positive loadings. Many genes in the cycle were strongly negatively loaded indicating that increased expression of genes involved in branched-chain amino acid degradation was associated with reduced MDI.

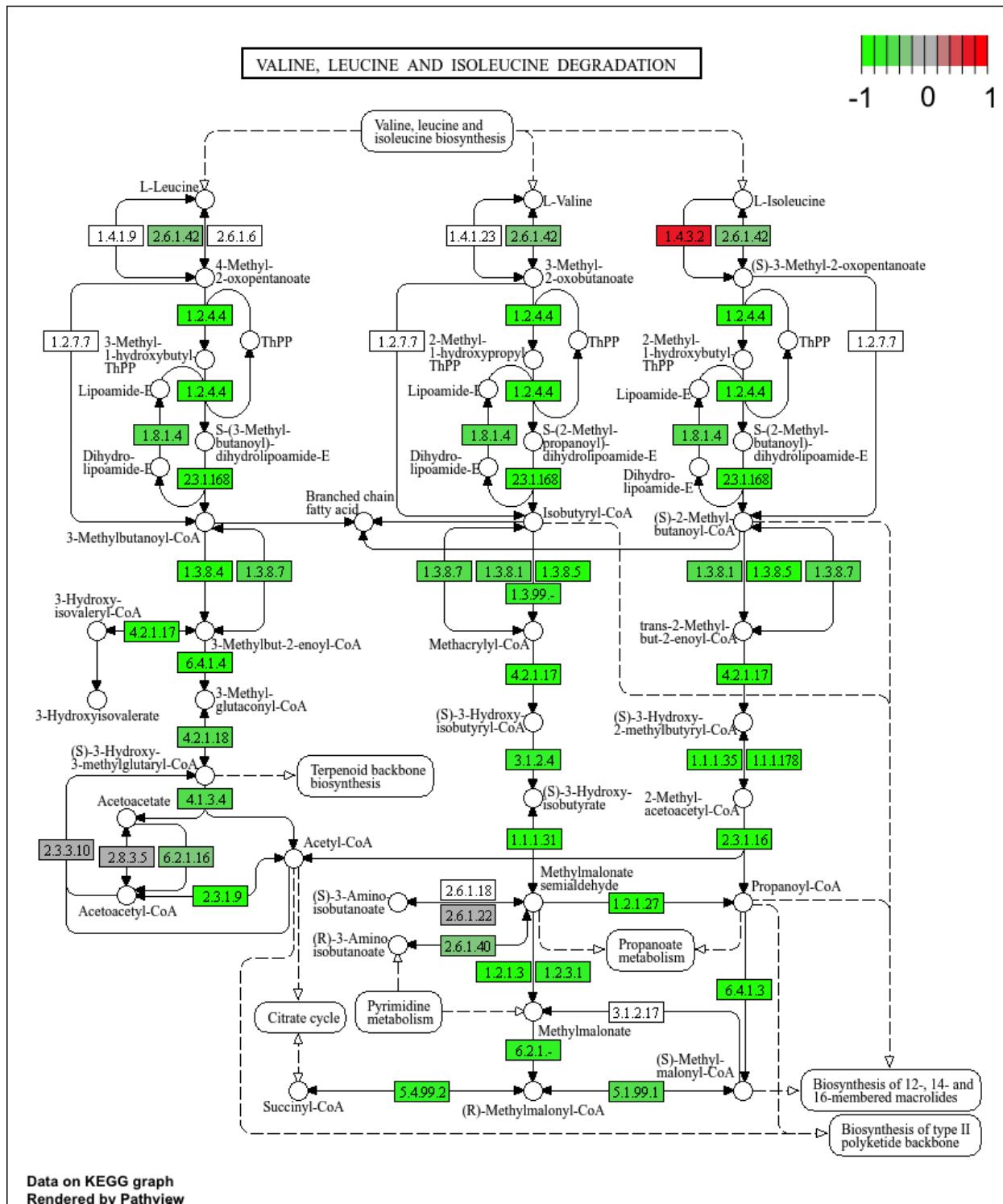


Figure S7: The KEGG pathway for branched-chain amino acid degradation in mice. Each element is colored based on its HDMA loading from adipose tissue normalized to run from -1 to 1. Genes highlighted in green had negative loadings, and those highlighted in red had positive loadings. Almost the entire pathway was strongly negatively loaded indicating that increased expression of genes involved in branched-chain amino acid degradation was associated with reduced MDI.

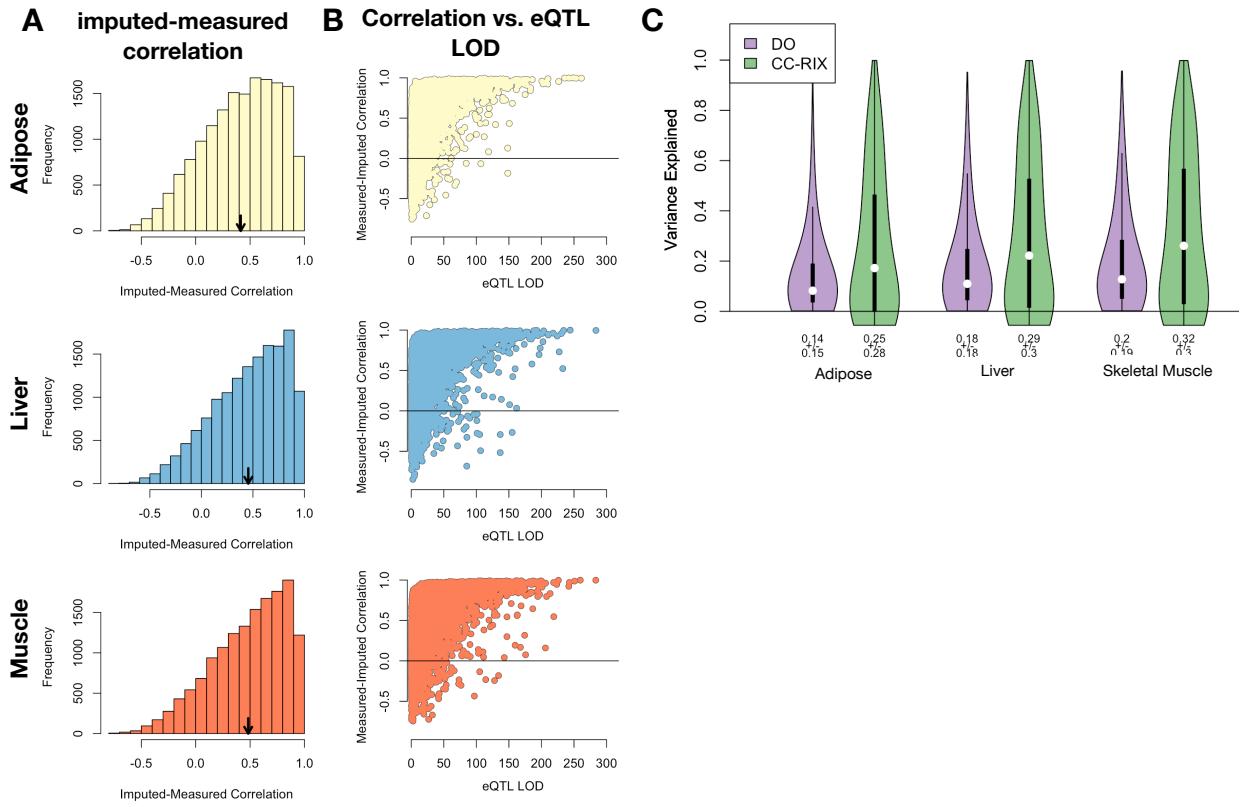


Figure S8: Validation of transcript imputation in the CC-RIX. **A.** Distributions of correlations between imputed and measured transcripts in the CC-RIX. The mean of each distribution is shown by the red line. All distributions were skewed toward positive correlations and had positive means near a Pearson correlation (r) of 0.5. **B.** The relationship between the correlation between measured and imputed expression in the CC-RIX (x-axis) and eQTL LOD score. As expected, imputations are more accurate for transcripts with strong local eQTLs. **C.** Variance explained by local genotype in the DO and CC-RIX.

| id | norm_ss | cell_iname | pert_type | raw_ss▲ | fdr_q_nlog10 | set_type | src_set_id |
|-----------|----------------|-------------------|------------------|----------------|---------------------|-----------------|-----------------------------------|
| | | HA1E | TRT_CP | -0.97 | 15.65 | PCL | CP_PROTEIN_SYNTHESIS_INHIBITOR |
| | | PC3 | TRT_SH.CGS | -0.90 | 15.65 | PATHWAY_SET | BIOCARTA_EIF4_PATHWAY |
| | | A375 | TRT_CP | -0.87 | 15.65 | MOA_CLASS | RAF_INHIBITOR |
| | | HCC515 | TRT_CP | -0.84 | 15.65 | PCL | CP_TOPOISOMERASE_INHIBITOR |
| | | HEPG2 | TRT_SH.CGS | -0.82 | 15.65 | PATHWAY_SET | BIOCARTA_BCR_PATHWAY |
| | | PC3 | TRT_CP | -0.77 | 15.65 | MOA_CLASS | MTOR_INHIBITOR |
| | | HCC515 | TRT_CP | -0.76 | 15.65 | PCL | CP_GLUCOCORTICOID_RECECTORAGONIST |
| | | HCC515 | TRT_CP | -0.76 | 15.65 | MOA_CLASS | GLUCOCORTICOID_RECECTORAGONIST |
| | | A375 | TRT_CP | -0.72 | 15.65 | MOA_CLASS | MTOR_INHIBITOR |
| | | -666 | TRT_CP | -0.70 | 15.65 | PCL | CP_PROTEIN_SYNTHESIS_INHIBITOR |
| | | -666 | TRT_CP | -0.68 | 15.65 | PCL | CP_JAK_INHIBITOR |
| | | A549 | TRT_CP | -0.67 | 15.65 | PCL | CP_GLUCOCORTICOID_RECECTORAGONIST |
| | | A549 | TRT_CP | -0.67 | 15.65 | MOA_CLASS | GLUCOCORTICOID_RECECTORAGONIST |
| | | -666 | TRT_CP | -0.57 | 15.65 | PCL | CP_MTOR_INHIBITOR |
| | | -666 | TRT_CP | -0.55 | 15.65 | MOA_CLASS | MTOR_INHIBITOR |
| | | -666 | TRT_CP | -0.55 | 15.65 | PCL | CP_PI3K_INHIBITOR |
| | | -666 | TRT_CP | 0.85 | 15.65 | MOA_CLASS | PKC_ACTIVATOR |

Figure S9: CMAP results using the *adipose* tissue composite transcript as an input. Table includes results from *all cell types* sorted with a $-\log_{10}(q) > 15$. The results are sorted by the correlation of the query to the input with the most negative results at the top.

| id | norm_CS | cell_iname | pert_type | raw_CS▲ | fdr_q_nlog10 | set_type | src_set_id |
|------|---------|------------|------------|---------|--------------|--------------------------------------------------------------|------------|
| | | VCAP | TRT_SH.CGS | -0.99 | 15.65 | PATHWAY_SET REACTOME_DOWNSTREAM_TCR_SIGNALING | |
| | | VCAP | TRT_SH.CGS | -0.99 | 15.65 | PATHWAY_SET REACTOME_NOD1_2_SIGNALING_PATHWAY | |
| | | A549 | TRT_SH.CGS | -0.92 | 15.65 | PATHWAY_SET BIOCARTA_TNFR1_PATHWAY | |
| | | VCAP | TRT_SH.CGS | -0.92 | 15.65 | PATHWAY_SET HALLMARK_WNT_BETA_CATENIN_SIGNALING | |
| | | HT29 | TRT_CP | -0.92 | 15.65 | PCL CP_TUBULIN_INHIBITOR | |
| -666 | | | TRT_OE | -0.88 | 15.65 | PCL OE_CELL_CYCLE_INHIBITION | |
| | | VCAP | TRT_SH.CGS | -0.87 | 15.65 | PATHWAY_SET REACTOME_P75_NTR_RECECTOR_MEDIATED_SIGNALLING | |
| | | HT29 | TRT_CP | -0.86 | 15.65 | MOA_CLASS TUBULIN_INHIBITOR | |
| | | MCF7 | TRT_CP | -0.85 | 15.65 | PCL CP_TUBULIN_INHIBITOR | |
| -666 | | | TRT_CP | -0.81 | 15.65 | PCL CP_PROTEASOME_INHIBITOR | |
| -666 | | | TRT_SH.CGS | -0.80 | 15.65 | PATHWAY_SET REACTOME_DOWNREGULATION_OF_ERBB2_ERBB3_SIGNALING | |
| | | HCC515 | TRT_CP | -0.80 | 15.65 | PCL CP_GLUCOCORTICOID_RECECTORAGONIST | |
| | | HCC515 | TRT_CP | -0.80 | 15.65 | MOA_CLASS GLUCOCORTICOID_RECECTORAGONIST | |
| | | A549 | TRT_OE | -0.78 | 15.65 | PATHWAY_SET REACTOME_RAF_MAP_KINASE CASCADE | |
| | | A549 | TRT_OE | -0.78 | 15.65 | PATHWAY_SET PID_RAS_PATHWAY | |
| -666 | | | TRT_SH.CGS | -0.78 | 15.65 | PCL KD_RIBOSOMAL_40S_SUBUNIT | |
| | | A549 | TRT_OE | -0.76 | 15.65 | PATHWAY_SET REACTOME_SIGNALLING_TO_P38_VIA_RIT_AND_RIN | |
| | | A549 | TRT_OE | -0.76 | 15.65 | PATHWAY_SET REACTOME_PROLONGED_ERK_ACTIVATION_EVENTS | |
| | | A549 | TRT_OE | -0.73 | 15.65 | PATHWAY_SET PID_TCR_RAS_PATHWAY | |
| | | HA1E | TRT_OE | -0.73 | 15.65 | PATHWAY_SET REACTOME_SHC RELATED_EVENTS | |
| | | HA1E | TRT_OE | -0.71 | 15.65 | PATHWAY_SET PID_EPHB_FWD_PATHWAY | |
| -666 | | | TRT_CP | -0.70 | 15.65 | MOA_CLASS GLYCOGEN_SYNTHASE_KINASE_INHIBITOR | |
| | | HA1E | TRT_OE | -0.70 | 15.65 | PATHWAY_SET PID_GMCSF_PATHWAY | |
| | | A549 | TRT_OE | -0.69 | 15.65 | PATHWAY_SET REACTOME_SIGNALLING_TO_ERKS | |
| -666 | | | TRT_LIG | -0.69 | 15.65 | PATHWAY_SET PID_ERBB_NETWORK_PATHWAY | |
| -666 | | | TRT_CP | -0.67 | 15.65 | MOA_CLASS PROTEASOME_INHIBITOR | |
| -666 | | | TRT_CP | -0.66 | 15.65 | PCL CP_GLYCOGEN_SYNTHASE_KINASE_INHIBITOR | |
| -666 | | | TRT_CP | 0.73 | 15.65 | MOA_CLASS MTOR_INHIBITOR | |

Figure S10: CMAP results using the *pancreatic islet* tissue composite transcript as an input. Table includes results from *all cell types* sorted with a $-\log_{10}(q) > 15$. The results are sorted by the correlation of the query to the input with the most negative results at the top.

| id | norm_ss | cell_iname | pert_type | raw_ss ▲ | fdr_q_nlog10 | set_type | src_set_id |
|-----------|----------------|-------------------|------------------|-----------------|---------------------|-----------------|-----------------------------------------|
| | | ASC | TRT_CP | -0.94 | 0.79 | PCL | CP_PARP_INHIBITOR |
| | | ASC | TRT_CP | -0.94 | 0.79 | MOA_CLASS | PROTEIN_TYROSINE_KINASE_INHIBITOR |
| | | ASC | TRT_CP | -0.84 | 0.45 | MOA_CLASS | BTK_INHIBITOR |
| | | ASC | TRT_CP | -0.81 | 0.39 | MOA_CLASS | LEUCINE_RICH_REPEAT_KINASE_INHIBITOR |
| | | ASC | TRT_CP | -0.81 | 0.79 | PCL | CP_HSP_INHIBITOR |
| | | ASC | TRT_CP | -0.80 | 0.93 | PCL | CP_EGFR_INHIBITOR |
| | | ASC | TRT_CP | -0.79 | 0.32 | MOA_CLASS | T-TYPE_CALCIUM_CHANNEL_BLOCKER |
| | | ASC | TRT_CP | -0.79 | 1.09 | PCL | CP_MTOR_INHIBITOR |
| | | ASC | TRT_CP | -0.76 | 0.97 | PCL | CP_PI3K_INHIBITOR |
| | | ASC | TRT_CP | -0.75 | 0.20 | MOA_CLASS | HISTONE_DEMETHYLASE_INHIBITOR |
| | | ASC | TRT_CP | -0.74 | 0.42 | PCL | CP_IKK_INHIBITOR |
| | | ASC | TRT_CP | -0.74 | 0.83 | PCL | CP_AURORA_KINASE_INHIBITOR |
| | | ASC | TRT_CP | -0.74 | 0.17 | PCL | CP_LEUCINE_RICH_REPEAT_KINASE_INHIBITOR |
| | | ASC | TRT_CP | -0.72 | 0.36 | PCL | CP_BROMODOMAIN_INHIBITOR |
| | | ASC | TRT_CP | -0.71 | 1.09 | MOA_CLASS | TYROSINE_KINASE_INHIBITOR |
| | | ASC | TRT_CP | -0.70 | 0.82 | PCL | CP_PROTEIN_SYNTHESIS_INHIBITOR |
| | | ASC | TRT_CP | -0.67 | 0.69 | PCL | CP_SRC_INHIBITOR |
| | | ASC | TRT_CP | -0.67 | 0.81 | MOA_CLASS | AURORA_KINASE_INHIBITOR |
| | | ASC | TRT_CP | -0.65 | 0.89 | MOA_CLASS | FLT3_INHIBITOR |
| | | ASC | TRT_CP | -0.62 | 0.40 | MOA_CLASS | FGFR_INHIBITOR |
| | | ASC | TRT_CP | -0.59 | 0.66 | MOA_CLASS | MEK_INHIBITOR |
| | | ASC | TRT_CP | -0.59 | 0.13 | MOA_CLASS | SYK_INHIBITOR |
| | | ASC | TRT_CP | -0.58 | 0.01 | PCL | CP_PKC_INHIBITOR |
| | | ASC | TRT_CP | -0.58 | 0.65 | PCL | CP_HDAC_INHIBITOR |
| | | ASC | TRT_CP | -0.58 | 0.65 | PCL | CP_ATPASE_INHIBITOR |
| | | ASC | TRT_CP | -0.53 | 0.09 | PCL | CP_FLT3_INHIBITOR |
| | | ASC | TRT_CP | -0.53 | 0.42 | PCL | CP_P38_MAPK_INHIBITOR |
| | | ASC | TRT_CP | -0.53 | 0.22 | MOA_CLASS | IKK_INHIBITOR |
| | | ASC | TRT_CP | -0.52 | 0.58 | PCL | CP_VEGFR_INHIBITOR |
| | | ASC | TRT_CP | -0.51 | -0.00 | PCL | CP_T-TYPE_CALCIUM_CHANNEL_BLOCKER |

Figure S11: CMAP results using the *adipose* tissue composite transcript as an input. Table includes the top 30 results derived *only from normal adipocytes* (ASC) regardless of significance. The results are sorted by the correlation of the query to the input with the most negative results at the top.

| id | norm_CS | cell_iname | pert_type | raw_CS ▲ | fdr_q_nlog10 | set_type | src_set_id |
|----|---------|------------|-----------|----------|--------------|-------------|---------------------------------------|
| | | YAPC | TRT_CP | -1.00 | 0.67 | MOA_CLASS | ABL_KINASE_INHIBITOR |
| | | YAPC | TRT_CP | -0.99 | 0.66 | PCL | CP_CDK_INHIBITOR |
| | | YAPC | TRT_CP | -0.97 | 1.41 | PCL | CP_TOPOISOMERASE_INHIBITOR |
| | | YAPC | TRT_CP | -0.95 | 0.70 | MOA_CLASS | THYMIDYLATE_SYNTHASE_INHIBITOR |
| | | YAPC | TRT_CP | -0.95 | 0.62 | MOA_CLASS | ADRENERGIC_INHIBITOR |
| | | YAPC | TRT_CP | -0.94 | 0.50 | MOA_CLASS | BENZODIAZEPINE_RECECTOR_ANTAGONIST |
| | | YAPC | TRT_CP | -0.89 | 0.63 | PCL | CP_RIBONUCLEOTIDE_REDUCTASE_INHIBITOR |
| | | YAPC | TRT_CP | -0.88 | 0.52 | MOA_CLASS | VASOPRESSIN_RECECTOR_ANTAGONIST |
| | | YAPC | TRT_CP | -0.85 | 0.63 | MOA_CLASS | ANGIOTENSIN_RECECTOR_ANTAGONIST |
| | | YAPC | TRT_CP | -0.85 | 0.33 | PCL | CP_CANNABINOID_RECECTORAGONIST |
| | | YAPC | TRT_CP | -0.84 | 0.30 | PCL | CP_RETINOID_RECECTORAGONIST |
| | | YAPC | TRT_CP | -0.83 | 1.19 | MOA_CLASS | NFKB_PATHWAY_INHIBITOR |
| | | YAPC | TRT_CP | -0.83 | 0.54 | MOA_CLASS | DNA_ALKYLATING_DRUG |
| | | YAPC | TRT_CP | -0.80 | 0.50 | MOA_CLASS | CHOLESTEROL_INHIBITOR |
| | | YAPC | TRT_CP | -0.79 | 0.15 | MOA_CLASS | SULFONYLUREA |
| | | YAPC | TRT_CP | -0.78 | 0.52 | MOA_CLASS | HIV_INTEGRASE_INHIBITOR |
| | | YAPC | TRT_CP | -0.78 | 0.13 | MOA_CLASS | LEUKOTRIENE_INHIBITOR |
| | | YAPC | TRT_CP | -0.78 | 0.45 | PCL | CP_PPAR_RECECTORAGONIST |
| | | YAPC | TRT_CP | -0.78 | 0.54 | MOA_CLASS | INSULIN_SENSITIZER |
| | | YAPC | TRT_CP | -0.77 | 0.51 | MOA_CLASS | ESTROGEN_RECECTOR_ANTAGONIST |
| | | YAPC | TRT_CP | -0.77 | 0.76 | MOA_CLASS | DNA_SYNTHESIS_INHIBITOR |
| | | YAPC | TRT_XPR | -0.77 | 0.67 | PATHWAY_SET | BIOCARTA_PARKIN_PATHWAY |
| | | YAPC | TRT_CP | -0.77 | 0.51 | PCL | CP_VEGFR_INHIBITOR |
| | | YAPC | TRT_CP | -0.75 | 0.39 | MOA_CLASS | RNA_SYNTHESIS_INHIBITOR |
| | | YAPC | TRT_CP | -0.72 | 0.60 | MOA_CLASS | BCR-ABL_KINASE_INHIBITOR |
| | | YAPC | TRT_XPR | -0.71 | 0.66 | PATHWAY_SET | BIOCARTA_EIF_PATHWAY |
| | | YAPC | TRT_XPR | -0.69 | 0.54 | PATHWAY_SET | PID_CIRCADIAN_PATHWAY |
| | | YAPC | TRT_CP | -0.68 | 0.77 | MOA_CLASS | TOPOISOMERASE_INHIBITOR |
| | | YAPC | TRT_XPR | -0.64 | 0.49 | PATHWAY_SET | BIOCARTA_CBL_PATHWAY |
| | | YAPC | TRT_CP | -0.64 | 0.53 | MOA_CLASS | TUBULIN_INHIBITOR |

Figure S12: CMAP results using the *pancreatic islet* composite transcript as an input. Table includes the top 30 results derived *only from YAPC cells*, which are derived from pancreatic carcinoma cells. Results are shown regardless of significance and are sorted by the correlation of the query to the input with the most negative results at the top.

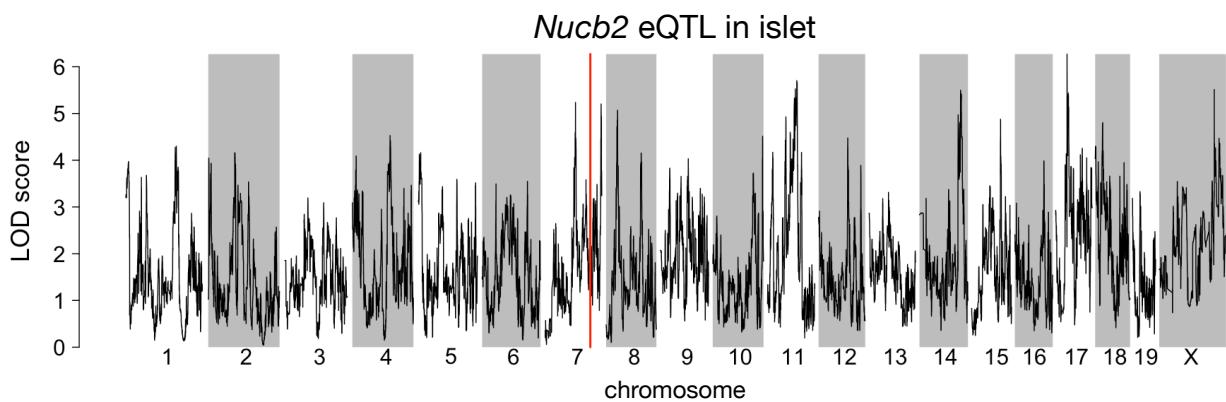


Figure S13: Regulation of *Nucb2* expression in islet. *Nucb2* is encoded on mouse chromosome 7 at 116.5 Mb (red line). In islets the heritability of *Nucb2* expression levels is 69% heritable. This LOD score trace shows that there is no local eQTLs at the position of the gene, nor any strong distal eQTL anywhere else in the genome.

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