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Department of Biology

HONOURS B.Sc. BIOMEDICAL SCIENCE, OPTION IN BIostatISTICS

Development and Testing of an Optimal Cardiometabolic Genetic
Risk Score to Predict Coronary Artery Disease Risk

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Preface

Throughout my undergraduate degree, I have made my fair share of mistakes. In truth, I have made many people's share of mistakes. Like the Rolling Stones, these failures have not always been what I wanted, but oftentimes they were exactly what I needed. This thesis represents the culmination of thousands of lessons taught to me by some truly incredible people.

I would first like to thank Professor Aris-Brosou for taking a chance on a Biomedical Science student first year who knew nothing about programming or statistics, without whom my life would doubtlessly be very different.

I would also like to thank Majid Nikpay, who has been a mentor to me for all of the years I have been researching statistical genetics.

Additionally, I would like to thank all of my friends for the support and motivation they have provided throughout my degree. In particular, I would thank Aaron R. Shifman. He has been a comrade in a lonely field, and a sounding board for my oftentimes less than genius ideas.

My most heartfelt thanks goes out to my girlfriend of four years, Kennedy Hao. She has motivated me to continue on no matter the obstacle and has proven time and again to be my closest ally, no matter the battle.

Through any and all obstacles, I have had no further to look for support than to my family. They have helped me through stress, desperation, and have been the only reason I have been able to accomplish the things that I have. Without them, nothing else would be possible.

My final acknowledgment is to my supervisor, Dr. Ruth McPherson. Working with her has been doubtlessly one of the single best decisions of my life. Three years have passed and yet Dr. McPherson continues to help me more in my career and my personal life than I could ever expect of anyone. Truly any success I may claim in the future will be a direct consequence of Dr. McPherson's kindness, generosity, and time.

To everyone, both named and not, I give my most heartfelt thanks.

CHRISTOPHER B. COLE

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May 2016

Dedication

I, Christopher B. Cole, declare that any and all work presented or implied in this thesis is my own original work and has not been previously presented or submitted for academic publication.

Abstract

Background and Rationale: Coronary artery disease (CAD) is a major cause of morbidity and mortality and much international effort has been expended to detect risk factors, both heritable and environmental. Although there is a well established genetic basis for CAD, genome wide association studies (GWAS) have identified just 46 common loci, explaining only a small fraction (13%) of the predicted heritability of CAD, estimated by twin studies to be between 40 and 60%. This “missing heritability” may be explained by diverse phenomenon including multiple common variants of very low effect size that may act via multiple causal risk factors for CAD and escape detection in sample sizes investigated to date, rare variants (MAF < 1%) of high effect size, gene × gene (G×G) interactions, and gene × environment (G × E) interactions. Previous efforts have tested the ability of a genetic risk score based on from 13 to 30 CAD-associated single nucleotide polymorphisms (SNPs) to predict CAD risk. Even this small number of risk alleles was shown to have significant predictive power and recently, to identify individuals who would benefit most from statin therapy to reduce LDL concentrations. However, improvements in genetic risk assessment are necessary and feasible given recent genetic advancements.

Purpose and Specific Objectives: This study hopes to develop an improved genetic risk score for coronary artery disease using a panel of independent risk loci. We address whether or not a panel of 202 independent SNPs with stepwise addition of cardiometabolic condition SNPs significantly predicts CAD.

Materials and Methods: 202 Independent SNPs were identified through GWAS and linear regression with multidimensional scaling in PLINK. The present study will use a stepwise logistic regression model with principal components and additional covariates. The independent variable will be a composite of genetic risk equal to a weighted sum of risk alleles with mean value imputation. The study will also compute Nagelkerke’s Pseudo-R² as a proxy measure for goodness of fit of the model. Additionally, we will compute the receiver operator characteristic curve and calculate the area under the curve to determine model predictive accuracy. The net recombination index will also be calculated for each model. Accurate multiple correction will be performed with respect to the correlation matrix between tests. Additionally, the above

analysis will be repeated using different FDR thresholds using the R program PRSice.

Results: This study will result in several metrics describing the model's ability to predict CAD in a population. If the predictive ability of our score is meaningful, it will allow clinical researchers to diagnostically determine individual risk to CAD.

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List of Acronyms

AIC Akaike Information Criterion	21
CAD Coronary Artery Disease	vii
PRS Polygenic Risk Score.....	vi
oPRS Optimal Polygenic Risk Score.....	vii
CARDIOGRAMC4D Coronary ARtery DIsease Genome wide Replication and Meta analysis plus The Coronary Artery Disease Genetics.....	1
GWAS Genome wide Association Study.....	vii
GLC Global Lipids Consortium	1
GIANT The Genetic Investigation of ANthropometric Traits	1
BMI Body Mass Index	vii
MI Myocardial Infarction	2
kb kilobase.....	2
DNA Deoxyribonucleic acid	4
A Adenine	4
C Cytosine.....	4
T Thymine.....	4
G Guanine.....	4

locus specific genetic location	4
CNV copy number variant	4
InDel insertion/deletion	4
RNA ribonucleic acid	4
SNP single nucleotide polymorphism	4
LD linkage disequilibrium	6
FWER family wise error rate	7
FDR false discovery rate	7
PRDS positive regression dependence on subsets	7
OR odds ratio	5
TG triglyceride	13
HDLc high density lipoprotein cholesterol	13
LDLc low density lipoprotein cholesterol	13
CMB cardiometabolic	15
AUC area under the curve	19
ROC receiver operator characteristic	23
OHGS Ottawa Heart Genomics Study	20
TRS traditional risk score	10

A note on notation

Throughout this thesis, the following conventions for notation are used.

1. A hat ($\hat{\cdot}$) denotes the estimator of a variable (i.e. $\hat{\beta}$ is the estimator of β).
2. Underlining a variable ($\underline{\cdot}$) implies that it is a n -vector, or $n \times 1$ dimensional matrix.

(i.e. $\underline{Y} = \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}$ is a $n = 3$ -vector).

3. Bolding indicates a matrix (i.e. $\mathbf{G} = \begin{bmatrix} 1 & \dots & 1 \\ \vdots & \ddots & \vdots \\ 1 & \dots & 1 \end{bmatrix}$)

As the efficiency and accuracy of rapid genome sequencing skyrockets, the potential for personalized therapies has made its way from science fiction to scientific reality. Using genetics to understand, diagnose, and eventually to predict illness is not a new idea; in recent years, however, technological ability and scientific understanding have advanced to such a point that researchers may predict risk for several diseases with reasonable confidence. Increasingly, variants in the human genome are being identified as being robustly linked to risk for complex illnesses such as heart disease [cite 9p21], obesity [cite fto], and schizophrenia [cite something]. However, much work remains to be done in order to create tools which may accurately predict individual disease risk from known and unknown genetic risk factors. In this thesis, we propose a novel extension to a well known methodology in order to better characterize disease risk from comorbid conditions using only summary statistics.

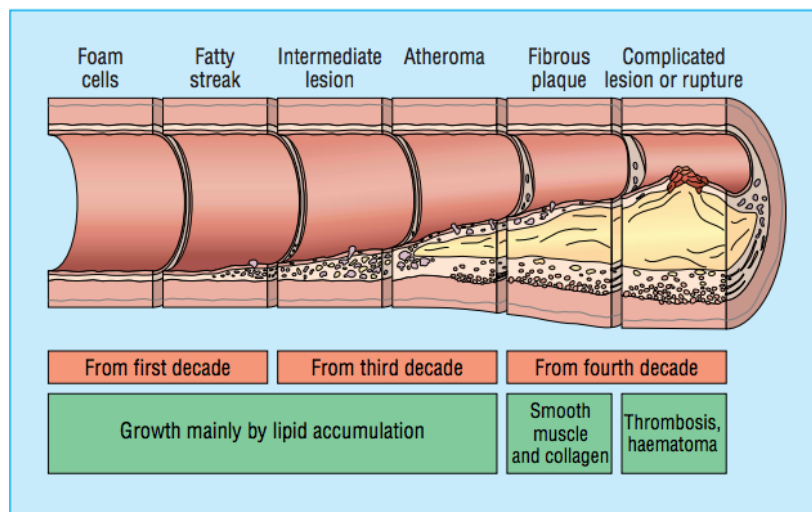
In brief, we present preliminary evidence for the use of PRSs in predicting CAD. We use recently published summary statistics from a GWAS conducted by the *Coronary ARtery Disease Genome wide Replication and Meta analysis plus The Coronary Artery Disease Genetics* (CARDIOGRAMC4D) consortium alongside evidence gathered by the *Global Lipids Consortium* (GLC) and the *The Genetic Investigation of ANthropometric Traits* (GIANT) consortium for lipids and BMI *per se*. We use this data alongside previously identified variants to construct first a simplistic PRS using only genome wide statistically significant ($P_{Bonferroni} < 0.05$ or $q_{FDR} < 0.05$) variants, then expand our search to variants which may not be as robustly linked to phenotype. [Cite storey, BH, and dudbridge]. We use an empirical maximization approach and several strategies of mathematical optimization in order to construct an oPRS, then devise a novel technique for

integrating information from co-morbid oPRS diseases in order to better predict CAD in four cohorts comprising approximately $n = 12,000$ individuals

1.1 Genetics of Coronary Artery Disease

CAD occurs when the major blood vessels supplying the heart become diseased or damaged, often leading to severe complications such as *Myocardial Infarction* (MI) and death. [cite review articles] CAD is known to be a complex genetic disease with heritability estimated by twin studies between 40 and 60%. [mcPherson 2016, twin studies paper] Several important variants have been identified which have been shown to robustly increase risk to CAD by altering lipid transporting pathways, structural collagen bodies, and others factors. [cite]

FIGURE 1.1: Progression of the formation of plaque causing CAD. Adapted from Gretch 2003.

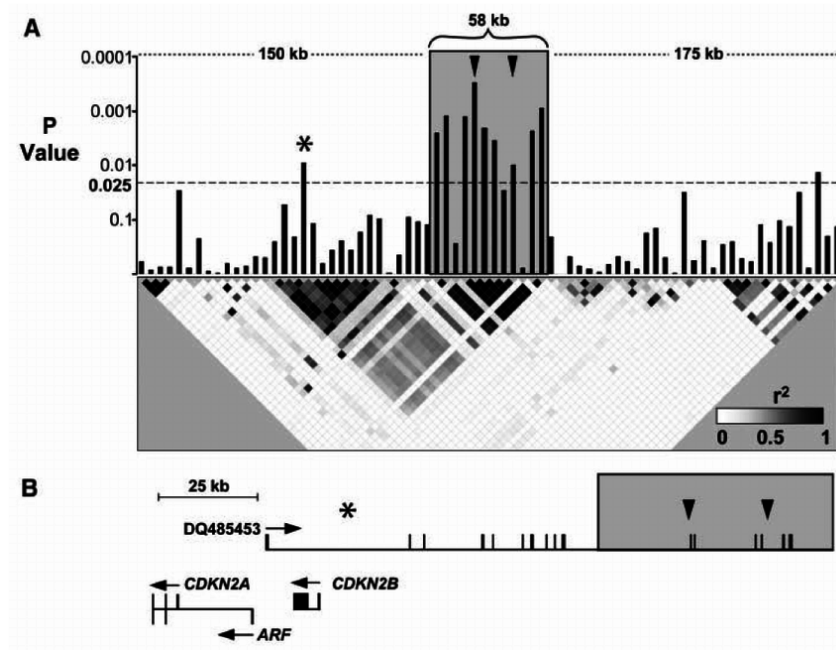


With heart disease and stroke the leading cause of prescription drug use in Canada as well as one of the leading causes of death and hospitalization [cite herat and stroke], the need to better understand, diagnose, and prevent this deadly disease is apparent. In order to better understand the need for improved statistical methodologies, it is important to understand the large body of previous attempts to characterize the genetic determinants of CAD

Despite some promising beginnings, initial attempts to understand and explain CAD through genetics were largely unsuccessful.[CITE] The first variant to be successfully and robustly linked to risk for CAD was the 9p21.3 locus. Discovered by a team of researchers at the University of Ottawa Heart institute, the allele consists of a 58 *kilobase* (kb) region on chromosome 9 which was

shown to be associated with CAD in a population of 23,000 Caucasian individuals. (McPherson and Tybjaerg-Hansen (2016))

FIGURE 1.2: Fine mapping of the genomic interval on chromosome 9 associated with Coronary Heart Disease. Adapted from Mcpherson et al 2006



This initial success began the era of the GWAS, explained in more detail in section 1.2. Researchers across the globe began frantically searching for more loci with the hope of understanding and predicting complex disease; in that goal, the GWAS has failed. (Visscher et al. (2012)) A number of important genetic markers for CAD have been discovered, but often in small familial cases or with very low effect sizes. [Cite] As the dust settles and the low hanging fruit have been picked, common variants have been shown to explain approximately 28% of the heritability of CAD [cite majid], yet a large portion remains to be accounted for. This has become known as the problem of “missing heritability” of complex disease; common genetic variants explain a relatively small portion of the total estimated heritability of a disease, therefore researchers must resort to ever more obscure and complex methods to attempt to explain the complex interactions between genetic elements in the human genome. [cite review paper] From pathway analysis to partitioned heritability to all kinds of arcane statistical procedures, researchers from across the globe have tried their hardest to shrink this gap between our knowledge and accurate prediction and understanding of complex disease. To this end, we develop our own methodology incorporating multiple sources of information for the more accurate prediction of clinical end points.

1.2 Genome Wide Association Studies

In order to properly introduce the model, however, the basic underpinnings must be explored and explained. Genome wide association studies seek to identify associations between individual genotypes and disease phenotypes in a hypothesis free manner. In this section, the statistical model required to understand GWAS is presented and explored.

1.2.1 Primer on Genetics

Deoxyribonucleic acid (DNA) is a double helical molecule which encodes the genetic blueprints for the construction of proteins and other materials that make up every known living organism. DNA is composed of three parts: a negatively charged phosphate group, a five carbon sugar *deoxyribose*, and (usually) one of four nitrogen bases. It is these bases, *Adenine* (A), *Cytosine* (C), *Thymine* (T), and *Guanine* (G) and their combinations which are under investigation in a GWAS. The specific combinations of these four bases in a *specific genetic location* (locus) determine the product produced by the DNA, and even a small change in this order can have large ramifications on the overall health, survival, and proper function of the organism.

1.2.2 Sequencing

DNA sequencing is the process of ascertaining a particular individual's genotype by means of chemical identification of the bases present at predefined sites. [cite] These sites, whether they be a change in a single base called a *single nucleotide polymorphism* (SNP), a variation in the number of tandem repeats of a small sequence named a *copy number variant* (CNV) or an *insertion/deletion* (InDel) of a sequence, may alter amino acid sequence, affect regulatory regions, or impact regulatory *ribonucleic acid* (RNA) sequences.

Definition 1.2.1 (Allele) *A specific form or subtype of a genetic locus. This could be one or more individual variations or a combination thereof.*

Remark 1 *Allele frequency is the frequency at which a particular allele occurs in the population. I.e. for locus A having n different alleles, the true population allele frequency of allele m is $\text{freq}A_m \equiv \frac{A_m}{\sum_{i=1}^n A_i}$, which is estimated in a sample population with a biased ratio estimator $\text{freq}\hat{A}_m \equiv \frac{\hat{A}_m}{\sum_{i=1}^n \hat{A}_i}$*

1.2.3 Statistical Definition

Consider a simple case control population where 1 defines case and 0 defines control. Define \mathbf{Y} as an n -vector where n denotes the number of individuals in a population and \mathbf{Y}_i gives the

individual's disease state. Additionally define G as an $m \times n$ matrix where m is the number of informative genotypic sites available with G_{ij} being the "state" (allele number) present at site j , $1 \leq i \leq m$, $i \in \mathbb{Z}^+$ in individual i , $1 \leq i \leq n$, $i \in \mathbb{Z}^+$.

$$\mathbf{Y} = \begin{bmatrix} Y_1 \\ \vdots \\ Y_n \end{bmatrix} \quad \mathbf{G} = \begin{bmatrix} G_{1,1} & \dots & G_{1,n} \\ \vdots & \ddots & \vdots \\ G_{m,1} & \dots & G_{m,n} \end{bmatrix}$$

In an additive genetic model, we define the phenotype \mathbf{Y} as a linear combination of \mathbf{G} weighted by a vector of $\underline{\beta}$ coefficient vectors estimated by regression analysis and $\underline{\epsilon}$ vector of errors. Express \mathbf{Y} such that

$$\mathbf{Y} = \underline{\beta}' \mathbf{G} + \underline{\epsilon} = \left(\sum_{i=1}^m \beta_i \mathbf{G}_{i,n} + \epsilon_n \right)'$$

$\underline{\beta}$ and $\underline{\epsilon}$ are approximated optimally by $\hat{\underline{\beta}}$ and $\hat{\underline{\epsilon}}$ in practice.

The purpose of a GWAS is not only to estimate these genetic effects $\underline{\beta}$ by $\hat{\underline{\beta}}$ but also to estimate their significance of association with phenotype vector \mathbf{Y} through a χ^2 test and corresponding test statistic m -vector $\hat{\chi}^2$. The degrees of freedom of this test statistic will vary between methods and models, and so will be left as further reading.

GWAS commonly estimate these effects through linear regression. The disease state (or disease level, should it be a continuous variable) is used as the response variable, while the main dependent variable is usually the number of minor alleles (0, 1, or 2) present. The β coefficient (for continuous disease state) or *odds ratio* (OR), therefore represents the average increase (for the continuous case) or the OR per additional risk allele present.

Remark 2 *This description assumes an additive genetic model, which states that the effect of possessing one minor allele is exactly the same as half the effect of having two risk alleles. Additional genetic models include the dominant scheme, where the effect of having two minor alleles is the same as having one minor allele, the recessive scheme where only the case of two minor alleles impacts the phenotype, and the general genetic model, where the effect of one allele is $a \times$ the effect of two alleles, $a \in [0, 1]$.*

By approximating $\underline{\chi}^2$ with $\hat{\underline{\chi}}^2$ and computing the corresponding P values, researchers are able to identify and quantify the effects of variants significantly ($P < 0.05$) associated with the phenotype. These results can be summarized in a Manhattan plot, named after the city of Manhattan with its high rise buildings towering over the scenery. The x axis of this plot is the genomic location

This may equivalently be described as the probability of making at least one false positive in M tests. This may alternatively be notated

$$Pr(V \geq 1) = 1 - (1 - \alpha)^M$$

Speaking asymptotically, $\lim_{M \rightarrow \infty} 1 - (1 - \alpha)^M = 1$ and false positives are guarenteed. It is against this backdrop that we recall in any relevant genetic context, M is large, and false positives are almost guarenteed.

There exist several ways to correct for this issue, chief among them is the widely adopted Bonferroni correction. Put simply, Bonferroni correction adjusts testing such that $Pr(V \geq 1) = \alpha$ rather than $1 - (1 - \alpha)^M$. It does so by rejecting all tests $p_i \in \underline{\mathbf{P}} | i \in 1 \dots M, i \in \mathbb{Z}^+$ such that

$$p_i \leq \frac{\alpha}{M}$$

The proof is not complex, but shall not be presented here for the sake of brevity. [cite bf] This adjustment (for $Pr(V \geq 1)$) is defined as control of the *family wise error rate* (FWER). This approach does not make any assumptions about the internal dependency strucutre of the tests, and as such, is conservative in the case of all categories of dependency. This is often undesired, as typically researchers will not prune their GWAS data to only independant variants. A more commonly accepted procedure, controlling the *false discovery rate* (FDR) rather than the FWER adjusts $\underline{\mathbf{P}}$ such that the proportion of false discoveries in all discoveries is controlled at α :

$$FDR \equiv E \left[\frac{V}{R} \right] = \alpha$$

This approach has the benefit of being adaptable and more powerful in circumstances of some forms of dependency (most notably *positive regression dependence on subsets* (PRDS) which is common scenario) and is most often applicable to GWAS where researchers are more willing to find more true positives at the cost of a fraction of false positives.

Therefore, in summation, GWAS is a statistical investigation which estimates several parameters given certain assumptions. Concepts presented in this section will be important background knowledge for the following sections, as most of our model builds off of these premeses.

1.3 Polygenic Prediction of Complex Disease

Referring to the defintions proposed in the previous section and recalling that in a general additive model, a phenotype vector $\underline{\mathbf{Y}}$ may be expressed as a linear combination of the $\underline{\beta}$ weighted genetic $n \times m$ -matrix \mathbf{G} and $\underline{\epsilon}$ following a standard normal $N(0, 1)$ distrbution:

$$\underline{\mathbf{Y}} = \underline{\beta}' \mathbf{G} + \epsilon$$

It has been previously proposed to combine genetic variants in order to crease a score S which encompasses estimated genetic effects in order to predict the phenotype vector $\underline{\mathbf{Y}}$. Define S for individual n :

$$S_n = \sum_{i=1}^m \beta_i G_{ni}$$

Note that in practice, our true statistics must be estimated. The logical estimator of $\underline{\beta}$ is the ordinary least squares regression estimator $\hat{\beta}$. There are other estimators, but the remainder of this section assumes this estimator. Our score is therefore described as:

$$\hat{S}_n = \sum_{i=1}^m \hat{\beta}_i G_{ni} \tag{1.1}$$

This score has several important properties which will be exploited in the below analysis. Note that in practice, $\underline{\beta}$

Notably, the non-centrality parameter of the χ^2 test for association between \hat{S} and $\underline{\mathbf{Y}}$ in the test population, assuming that $\hat{\beta}$ has been estimated in a training population of size n_1 and tested in a test population of size n_2 , is given by:

$$\lambda = \frac{n_2 R_{\hat{S}, Y}^2}{1 - R_{\hat{S}, Y}^2}$$

Where $R_{\hat{S}, Y}^2$ is the percent explained variance of the phenotype Y with the estimated score \hat{S} . Additionally, note that $E[\hat{S}] = 0$ and the second moment in a particular individual is given by

$$\begin{aligned} Var(\hat{S}) &= \sum_{i=1}^m Var(\hat{\beta}_i, G_i) \\ &= \sum_{i=1}^m \hat{\beta}_i^2 \\ &\approx m Var(\hat{\beta}_i) \end{aligned}$$

These mathematical properties become important later. These identities have been adapted from Dudbridge (2013).

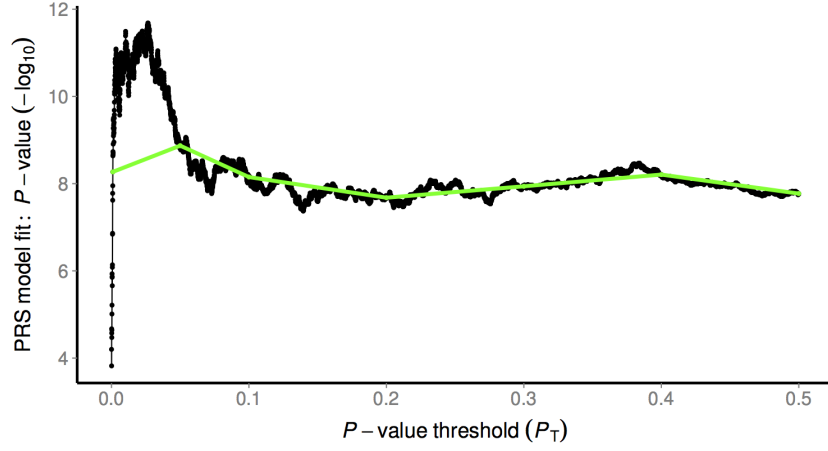
1.4 Optimal Polygenic Risk Scores

Frequently, not all m variants are used in the construction of the PRS though. Typically, researchers will type the top $m | P_m \leq \alpha_{adj}$ where α_{adj} denotes the shifted acceptance threshold after multiple

testing correction. We denote these variants as $m_{P \leq T}$ where T is the P value threshold.

Though these variants have the highest probability of being truly associated with the phenotype, constructing a score with this few SNPs misses the many small and insignificant effects hidden in marginally significant and insignificant hits. Thus, Euesden et al. (2014) have developed a method to find the best-fit PRS, that is, the PRS which maximizes genomic signal while minimizing noise as in 1.4. We denote this as the oPRS.

FIGURE 1.4: oPRS plot for schizophrenia predicting major depressive disorder status. Adapted from Euesden et al. (2014)



On a high level, this score involves iterating through a list of P value thresholds T , constructing a score using all $m_{P < T}$ and selecting either the smallest P value of association between \hat{S} and \underline{Y} or the highest $R^2_{\hat{S}, Y}$ to move in the analysis.

More formally, we fix individual n and construct a vector of estimated scores $\hat{\underline{S}}$ with length n_T equal to the number of attempted P value thresholds.

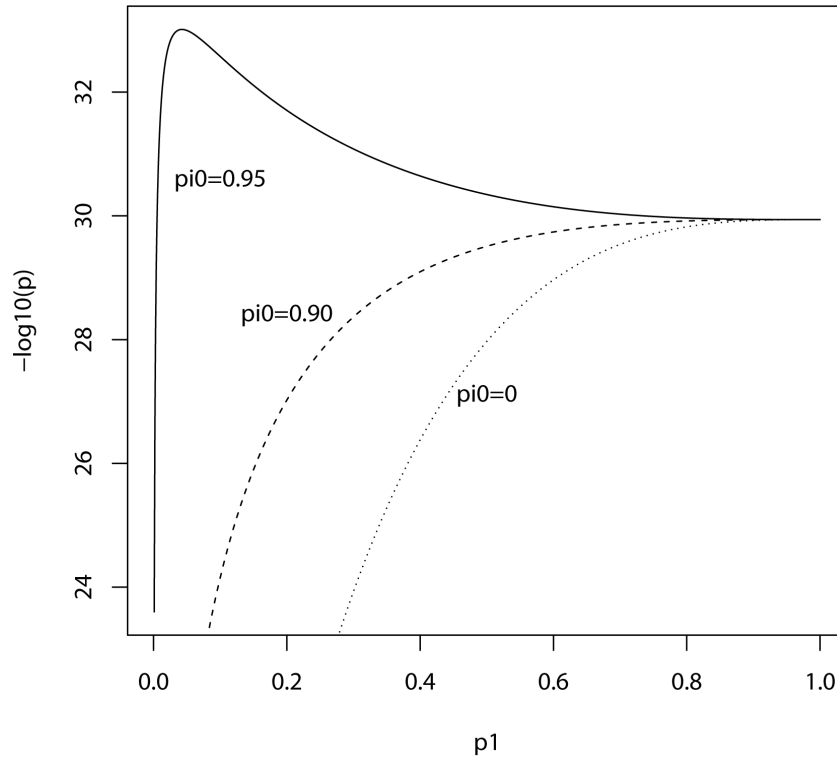
$$\hat{\underline{S}} \equiv \begin{bmatrix} \hat{S}_{T_1} \\ \vdots \\ \hat{S}_{n_T} \end{bmatrix} \quad \hat{S}_T = \sum_{i=1}^{m_{P \leq T}} \hat{\beta}_i G_{ni}$$

Note, however, that when we build a score at each threshold for each individual, an $n \times T$ matrix is constructed, where n is the number of individuals and T is the number of thresholds. The entries are the estimated score \hat{S}_{nT} for individual n at threshold T :

$$\hat{\mathbf{S}} = \begin{bmatrix} \hat{S}_{1,1} & \dots & \hat{S}_{1,T} \\ \vdots & \ddots & \vdots \\ \hat{S}_{n,1} & \dots & \hat{S}_{n,T} \end{bmatrix} \quad (1.2)$$

It is from the matrix described in 1.2 that the rest of our model will be built.

FIGURE 1.5: Expected $-\log_{10}(P)$ value of linear regression estimate as a function of P -value threshold for selecting markers into Polygenic score. Note that π_0 refers to the proportion of *true null* markers, that is, markers which have no effect on phenotype. (Dudbridge (2013))



Remark 3 Though it is always possible to construct an optimal score, only in certain circumstances is the P value threshold $P_T < 1$, depending on the internal structure of the disease under question. At different heritability levels, a disease may only have an optimal score with $P_T = 1$, as described in Figure 1.4.

1.5 Specific Aims

This study plans to address the following issues:

1. Characterize and evaluate the predictive accuracy of the traditional risk score (*traditional risk score* (TRS)). Evaluate summary statistics for regression models and perform a meta analysis across cohorts to estimate an overall effect for the model.
2. Propose two novel applications of PRS to better predict CAD. Develop these methods mathematically, validate them in test sets, and compare their performance to the traditional risk score.

3. Perform an exploratory analysis on secondary data to further evaluate the effectiveness of risk scores in predicting CAD.
4. Discuss possible theoretical ramifications of findings, applications, and further research.

2.1 Study Population

There are four major cohorts used as a “test” set in this study, comprising a total $n = 13371$.

Ottawa Heart Genomics Study (OHGS): Details of this cohort have been previously described (Davies et al., 2012). Both cases (1) and controls (0) were recruited from the Lipid Clinic at the University of Ottawa Heart Institute (UOHI). Cases with diabetes mellitus were entirely excluded. Cases were required to have at least one of: a stenosis in a major epicardial vessel of at least 50%; have had a percutaneous intervention (PCI); have had coronary artery bypass surgery (CABG); or have had a myocardial infarction (MI). Earlier studies using this cohort examined the effect of age, and cases were required to be ≤ 55 years old for men and ≤ 65 years old for women. The controls were either healthy elderly patients recruited from the catheterization laboratory or the UOHI; they had no stenosis $\geq 50\%$ in any major epicardial vessel and were required to be at minimum 65 years old for men and 70 years old for women. The study protocol was approved by the Human Research Ethics Board of the University of Ottawa Heart Institute and all participants provided informed consent.

Cleveland Clinic (CCGB): Cases and controls from the Cleveland Clinic Cohort followed the same collection procedure as outlined for OHGS except were collected at the catheterization laboratory of the Cleveland Clinic.

Duke Cathgen Study (DUKE): Both cases and controls were recruited from the catheterization laboratory at Duke University. Cases were required to have at least one epicardial coronary vessel with $\geq 50\%$ stenosis while being at most 55 years old for males and 65 years old for females.

Controls were asymptomatic and required to have $\leq 30\%$ stenosis in all coronary vessels. Subjects with diabetes mellitus, severe pulmonary hypertension or congenital heart disease were excluded. The study protocol was approved by the ethics committee and all participants provided informed consent.

INTERHEART Cohort (ITH): INTERHEART is a standardized case-control study of acute myocardial infarction from across the world. Only Caucasian participants were analyzed in this study due to issues with differing gene frequencies among ethnicities. Cases – those showing acute MI, were age matched to within 5 years of controls who were community based individuals with no previous history or diagnosis of heart disease and exertional chest pain. The study protocol was approved by the ethics committees in all participating centers and all participants provided informed consent. A full list of ITH investigators is found at <http://www.phri.ca/interheart/index2.html>.

2.2 Genotyping and Imputation

SNP genotyping of the above cohorts was performed on either Affymetrix 6.0 or 500K chip arrays at the University of Ottawa Heart Institute using the recommended procedure from the manufacturer. They were processed as in Dandona et al. (2010); Schunkert et al. (2011). Imputation was performed using IMPUTE2 and the August 2009 1000 Genomes reference panel. (Howie et al., 2009). Approximately 5.5 million SNP passed quality control measures including $\text{info} > 0.5$, Hardy Weinburg Equilibrium $> 1 \times 10^{-6}$ and missingness $< 10\%$.

2.3 Training Populations

This study additionally comprised two “training” populations which were used to estimate the $\hat{\beta}$ effects necessary for the construction of PRS.

GIANT Consortium: GIANT consortium attempts to identify genetic loci which may modulate human body size, height, and obesity. We use for this study their data on BMI predicting SNP calculated from approximately $n = 123,865$ on close to 2M SNPs. Collection methodologies and specific information is outlined in Speliotes et al. (2010).

Global Lipids Consortium: The Global Lipids Consortium estimates genetic effects in $n = 188,577$ individuals using whole genome and custom genotyping arrays. We use their estimated additive genetic effects for SNPs predicting *triglyceride* (TG), *high density lipoprotein cholesterol* (HDLc), and *low density lipoprotein cholesterol* (LDLc). Collection methodologies and further information are outlined in (Consortium, 2013).

CARDIoGRAMplusC4D: The Coronary ARtery DIsease Genome wide Replication and Meta-analysis (CARDIoGRAM) plus The Coronary Artery Disease (C4D) Genetics is a collaborative effort combining GWAS data from multiple data sources to better estimate potential genetic effects in CAD. Their data represents 22 studies with 22,233 cases and 64,762 controls of European individuals. Further information and collection methodology is outlined in The CARDIoGRAM-plusC4D Consortium (2015).

2.4 Polygenic Prediction of CAD

In the following analysis we primarily compare three different methods for constructing PRS \hat{S} .

2.4.1 Traditional Risk Score

The first, which we denote as the “traditional risk score”, or \hat{S}_{TRS} . This score uses the “traditional” approach of only using the highest confidence genome wide significant loci for CAD in the construction of the score. We derive the estimated $\hat{\beta}$ effects from (The CARDIoGRAMplusC4D Consortium, 2015), whose methodology is described above. We only use the 212 variants from this section which have been shown to be FDR significant with $q < 0.05$ across the whole genome, as is common practice. Recall from the derivation leading up to equation 1.1 that PRS S for individual n is described as

$$S = \sum_{i=1}^m \beta_i G_{ni}$$

Therefore for this score, we define $\hat{\beta}$ as a vector of length 212 with each of the estimated additive genetic effects derived from CARDIoGRAM plus C4D, and construct estimated score \hat{S} for individual n as

$$\hat{S}_{n,TRS} \equiv \sum_{i=1}^{212} \hat{\beta}_i \mathbf{G}_{n,i}$$

This forms the basis for our first model.

2.4.2 Cardiometabolic Risk Score

The second score which we estimate is a novel derivation. We aim to use genetic information from several co-morbid conditions together to better explain CAD. The motivation is that important signals may be spuriously insignificant in large meta analyses, or simply have too low effect to be accurately categorized as significant; taking information from co-morbid conditions allows researchers a wider span of information to integrate.

We use meta data from four co-morbid conditions to estimate the genetic effects of these traits and **re-prioritize** variants with the intention of creating a minimal score for CAD which better predicts the phenotype.

First, we introduce some new notation. We denote $\hat{\beta}_{LDLc}, \hat{\beta}_{HDLc}, \hat{\beta}_{TG}, \hat{\beta}_{BMI}$ as the vectors of estimated effects for LDLc, HDLc, TG, and BMI respectively derived from the training sets outlined in section 2.3.

We separately order variants by their P value and say m^* is the number of genome-significant significant ($q \leq 0.05$) hits found in each study. We take $1 \dots m^*$ from each data set and call this set of variants G^* for important genetic effects. We define the set G^* as containing all genetic elements G_i such that i is a part of our selected significant ordered set $1 \dots m^*$.

$$G^* \equiv \{G_i | i \in 1 \dots m^*\} \quad m^* | q < 0.05$$

We then take all genetic effects $i \in G^*$ and calculate a score based on these variants instead of the 212. We define this new *cardiometabolic* (CMB) score for any individual n as \hat{S}_{CMB} :

$$\hat{S}_{CMB} \equiv \sum_{i \in G_{LDLc}^*} \hat{\beta}_i G_{n,i} + \sum_{i \in G_{HDLc}^*} \hat{\beta}_i G_{n,i} + \sum_{i \in G_{TG}^*} \hat{\beta}_i G_{n,i} + \sum_{i \in G_{BMI}^*} \hat{\beta}_i G_{n,i}$$

We use this new score to predict CAD, with the hypothesis that incorporating several co-morbid conditions will better prioritize variants in order to achieve increased predictive accuracy.

2.4.3 Optimal Cardiometabolic Risk Score

We further extend this \hat{S}_{CMB} using oPRS as introduced in section 1.4. Instead of selecting m^* to be all variants such that $q < 0.05$, we select all P values such that $P < T_o$ where T_o is the optimal threshold found by iterating through P value thresholds for score inclusion.

$$G^* \equiv \{G_i | i \in 1 \dots m^*\} \quad m^* | P < T_o$$

And similarly construct our optimal cardiometabolic risk score as before:

$$\hat{S}_{oCMB} \equiv \sum_{i \in G_{LDLc}^*} \hat{\beta}_i G_{n,i} + \sum_{i \in G_{HDLc}^*} \hat{\beta}_i G_{n,i} + \sum_{i \in G_{TG}^*} \hat{\beta}_i G_{n,i} + \sum_{i \in G_{BMI}^*} \hat{\beta}_i G_{n,i}$$

This forms the new optimal score for testing.

2.5 Statistical Analysis

2.5.1 Construction of PRS

PRS were constructed in both R and Plink v1.90 (<https://www.cog-genomics.org/plink2>) with validation in Plink v 1.07 (<http://pngu.mgh.harvard.edu/~purcell/plink/>). Each of approximately 5.5M imputed, post quality control, GWAS were coded as 0,1, or 2, depending on the number of minor alleles present. PRS was calculated as described in previous sections and a normal distribution was validated using both empirical tests (Levene, Shapiro-Wilk) and qualitative observations on qq plots and histograms. Each PRS was confirmed to have a normal distribution, validating one of the assumptions of future models.

Optimal PRS (oPRS) were constructed again using R and Plink 1.90/1.07, though with the assistance of PRSice. (Euesden et al., 2014) To determine optimal thresholds for SNP inclusion, SNPs were ordered by P value and 2500 “slices” or thresholds were created between $P = 0.0001$ and $P = 0.25$. For each of these thresholds, a logistic regression model was created, as detailed below, and the P value of association was calculated. The model was adjusted for the first two principal components and sex. The maximal P value of association was observed and extracted. Based on permutation analysis in the original publication, since our oPRS showed P -values of association less than $\alpha = 0.001$, our association was deemed to be significant overcoming multiple testing correction. Results were graphically displayed using both base plotting in R and ggplot2.

2.5.2 Predictive Model

In order to predict CAD with our PRS, covariate adjusted logistic (binomial) regression models were used. Scores were always adjusted for the first two principal components to adjust for population stratification. Nagelkerke’s Pseudo R^2 , gives an estimation of the scaled explained variance of a logistic model. It is given by

$$R^2 = 1 - \left\{ \frac{L(M_{intercept})}{L(M_{full})} \right\}^{\frac{2}{N}}$$

Where $L(M)$ is the conditional probability of the outcome variable (CAD) given the independent variables and L is the likelihood function operator. A full description of the operator is given in Nagelkerke (1991).

Area under the receiver operator character curve, also known as the c -statistic, is a well known proxy for predictive accuracy of a binary model. It was calculated in the pROC package in R (Robin et al. (2011)). Differences between ROC model was assessed firstly by the method for correlated

ROC curves proposed by DeLong et al. (1988). A secondary, more robust, difference was estimated through 1000 bootstrap permutations of dependent variables in R.

Meta analysis was conducted in the metafor package in R. (Viechtbauer, 2010) Random effects were assumed for study variables to have greater applicability to the population at large.

2.6 Computational Resources

All analyses were performed at the Center for Advanced Computing, a large scale Red Hat Enterprise linux parallel computing cluster used to quickly analyze large sets of data. All analysis was parallelized either using inbuilt libraries or OpenMPI standards.

Analyses were performed in R version 3.2.3 (<https://www.r-project.org/>), Python legacy version 2.7.9 (<https://www.python.org/>), Plink (<http://pngu.mgh.harvard.edu/~purcell/plink/>), and GCTA (<http://cns.genomics.com/software/gcta/>).

All analysis was logged and stored securely and anonymously; back ups of all data were made and encrypted.

All analysis was version controlled using git + github and this thesis is entirely reproducible. Any code available upon request.

General characteristics of the study population are displayed in Table 3.1.

3.1 Traditional Risk Score

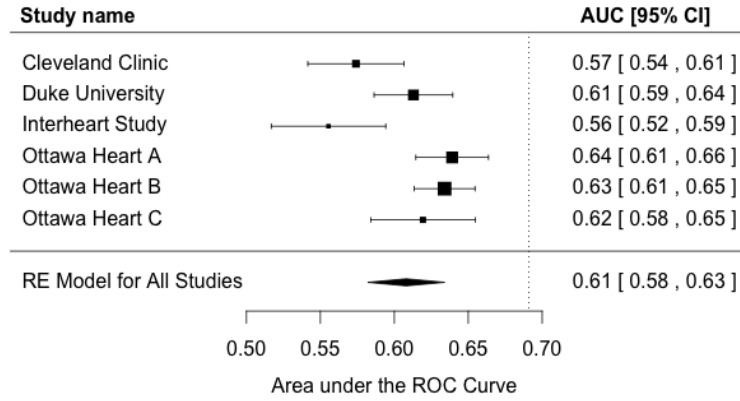
The traditional risk score was significantly ($P < 2.2 \times 10^{-16}$) associated with case/control status in all cohorts when adjusted for principal components to control for population stratification. (Price et al., 2006; Zhang et al., 2013). On average, scores between cases and control differed by $5.06 \times 10^{-4} \pm 1.73 \times 10^{-4}$. Full distributions of the score dependent on case control status are presented in Supplementary Figure 4.1. \hat{S}_{TRS} predicted CAD status better than chance in all cohorts. Area under the receiver operator characteristic curve was calculated for each model and

	All Participants	Cases	Controls
n	9663	5831	3832
Age ¹ (years)	62.8 \pm 12.3	56.2 \pm 10.1	73.0 \pm 7.4
Smoke Current (%)	29.6	36	20
Male (%)	65.3	76.7	47.9
Obese ² (%)	29	35.1	19.7
BMI (kg/m ²)	28.1 \pm 5.3	28.9 \pm 5.3	26.7 \pm 4.9
TG ³ (mmol/L)	1.46 \pm 1.47	1.66 \pm 1.70	1.18 \pm 0.99
HDLc ³ (mmol/L)	1.27 \pm 0.44	1.13 \pm 0.39	1.46 \pm 0.44
LDLc ³ (mmol/L)	3.29 \pm 1.08	3.18 \pm 1.17	3.43 \pm 0.93

Table 3.1: General Population description. All values are expressed as mean \pm one standard deviation unless otherwise noted. ¹ Age represents age at consent for controls and age at diagnosis for cases ² Obesity is defined as having a BMI of greater or equal to 30 kg/m² at time of collection ³T G (triglyceride), LDLc (low density lipoprotein cholesterol), HDLc (high density lipoprotein cholesterol).

meta-analysed. The resulting $AUC \pm 95\%$ confidence intervals are displayed in Figure 3.1.

FIGURE 3.1: Random effects meta analysis of AUC ROC from six cohorts.



Logistic regression was used to predict observations following the model. Summary statistics from the models employed are displayed in Table 3.2

$$CAD = X_0 + \hat{\beta}_1 \hat{S}_{TRS} + \hat{\beta}_2 PC_1 + \hat{\beta}_3 PC_3 + \epsilon$$

Add in abbreviations

Table 3.2: Summary statistics from Logistic association model.

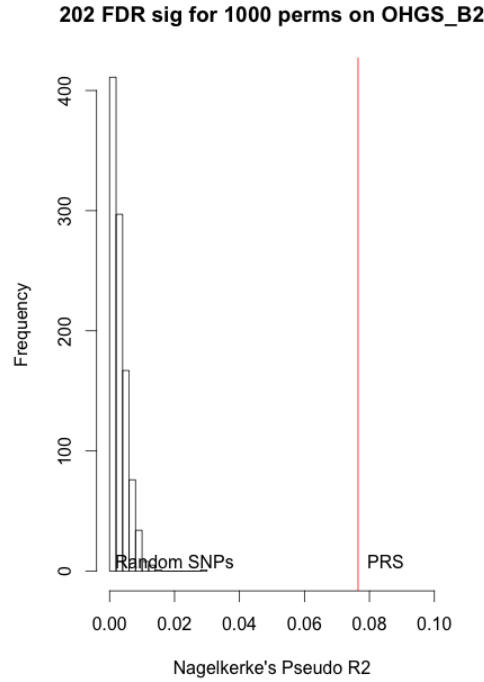
Cohort	OR	SE	R^2	AIC	AUC
Cleveland Clinic	153.89908	36.42776	0.01621871	1877.724	0.5740551
Duke University	255.78537	33.44304	0.04713465	2335.567	0.6129263
Interheart	83.95637	46.45943	0.01695232	1172.994	0.5554871
OHGS A2	310.49752	34.52749	0.07650691	2558.277	0.6391285
OHGS B2	259.59352	24.94511	0.07425403	3681.768	0.6339916
OHGS C2	276.96733	45.92012	0.05491302	1318.919	0.6193695

An *area under the curve* (AUC) ≥ 0.5 indicates that the model predicts CAD better than chance. The overall random effects meta analyzed AUC was 0.61 ± 0.03 for \hat{S}_{TRS} , with an average NagelKerke's Pseudo- R^2 of 0.047. Interheart was the worst fit model, with NagelKerke's Pseudo- $R^2 = 0.017$ and $AUC = 0.555$, barely predicting above chance. This is in contrast to the OHGS cohorts, which consistently fit better than Cleveland Clinic, Duke, or Interheart. As increasing the number of SNP in the score will always increase the fit of the model, we compare the 202 FDR significant loci to randomly selected loci in 1000 bootstraps in Figure 3.1.

The score remains significantly associated when adjusted for individual's sex, a known cardiovascular risk factor. The predictive accuracy of the model significantly increases after inclusion of sex, as would be expected. The random effects meta analysis AUC for all six cohorts becomes 0.69[0.62, 0.76].

In *Ottawa Heart Genomics Study* (OHGS) B2, sex significantly ($P = 0.00226$) interacts with the effect of the risk score. This shows that sex modulates the effect of genetics in this cohort. The remainder of the cohorts do not interact.

FIGURE 3.2: Score predicts better than chance



These results are in line with literature values. Those in the top quintile of the PRS were 70% more likely to have CAD than not (2045 cases vs 1198 controls). Similarly, those in the bottom quintile were 5% less likely to be diagnosed with CAD than not (1576 cases vs 1659 controls).

3.2 Cardiometabolic Risk Score

We add in each co-morbid score in a stepwise manner. $\hat{S}_{CMB;1}$ uses just the information available for CAD and is equivalent to the above section. $\hat{S}_{CMB;2}$ uses information from CAD and BMI, while $\hat{S}_{CMB;3}$ uses CAD, BMI, and LDLc. $\hat{S}_{CMB;4}$ uses information from CAD, BMI, LDLc, and TG, while $\hat{S}_{CMB;5}$ uses CAD, BMI, LDLc, TG, and HDLc. Note that in this section we restrict our

analysis to the OHGS cohorts along with Cleveland Clinic due to the lack of quality in lipid data present in the other cohorts.

The summary statistics of this analysis are presented in Table 3.3. Higher genetic risk scores were uniformly and significantly ($P < 2.2 \times 10^{-16}$) associated with increased risk of CAD.

Table 3.3: My caption

Score	Cohort	OR	SE	R2	AIC	AUC
$\hat{S}_{CMB;1}$	OHGS A2	310.49752	34.52749	0.07650691	2558.277	0.6391285
	OHGS B2	259.59352	24.94511	0.07425403	3681.768	0.6339916
	OHGS C2	276.96733	45.92012	0.05491302	1318.919	0.6193695
	Cleveland Clinic	153.89908	36.42776	0.01621871	1877.724	0.5740551
$\hat{S}_{CMB;2}$	OHGS_A2	252.9639	25.29332	0.09108544	2547.617	0.6555183
	OHGS_B2	267.348	22.48745	0.09187763	3654.756	0.6501946
	OHGS_C2	280.9237	38.98146	0.07687197	1300.585	0.6455279
	Cleveland	337.3714	35.18263	0.08387982	1791.596	0.6659644
$\hat{S}_{CMB;3}$	OHGS_A2	236.0145	26.17239	0.07656732	2570.063	0.6429851
	OHGS_B2	255.7401	24.09888	0.0767165	3688.513	0.6371506
	OHGS_C2	284.9796	41.16138	0.07121422	1305.337	0.640201
	Cleveland	344.9182	37.87978	0.07572764	1802.024	0.6546671
$\hat{S}_{CMB;4}$	OHGS_A2	266.5048	29.24856	0.07786803	2568.062	0.6442205
	OHGS_B2	270.8893	26.45495	0.07264458	3697.51	0.6330786
	OHGS_C2	298.9828	44.83843	0.06638254	1309.38	0.6337181
	Cleveland	372.189	41.80231	0.07218274	1806.542	0.6509422
$\hat{S}_{CMB;5}$	OHGS_A2	297.0165	34.10419	0.07234597	2576.54	0.6401786
	OHGS_B2	299.0699	30.76742	0.06720315	3709.488	0.6280858
	OHGS_C2	323.9172	50.90267	0.06088933	1313.958	0.6275034
	Cleveland	410.9963	48.57387	0.06493754	1815.742	0.6436849

In permutation analyses, each of the scores performed significantly better than an equivalent number of randomly selected SNPs in 1000 bootstraps. The random effects meta analysis AUC values were 0.65[0.64, 0.67], 0.64[0.63, 0.66], 0.64[0.63, 0.65], 0.63[0.62, 0.65] for scores 1 through 5 respectively. Interestingly, the more SNPs added in, the worse the model was at predicting the phenotype. The *Akaike Information Criterion* (AIC) is also uniformly smaller in score 2 than in subsequent scores, meaning that this model fit the data the best. Persons in the upper quintile of this score were 81% more likely (1725 cases vs 953 controls) to have CAD than not (compared to 70 % for the previous score) and people in the bottom quintile were 15.7% less likely (1240 cases vs 1471 controls) to have CAD than having it. There was also a substantive increase in Nagelkerke's Pseudo R^2 in the second score compared to any other, especially in the Cleveland cohort.

The score maintained its significance even after inclusion of biologically relevant covariates such as gender and smoking status. Additionally, the predictive accuracy of the score increased substantially after the inclusion of these covariates. After inclusion of individual's sex, a known cardiovascular risk factor, predictive accuracy increased substantially. The random effects meta analysis AUC values

were increased to 0.69[0.62, 0.76], 0.74[0.67, 0.81], 0.73[0.66, 0.81], 0.73[0.66, 0.81], 0.73[0.66, 0.80] for $\hat{S}_{CMB;1}$ through $\hat{S}_{CMB;5}$ respectively. Again it appears as though $\hat{S}_{CMB;2}$ is the best predictive model.

We additionally investigated whether sex significantly modulates the effect of $\hat{S}_{CMB;}$, and found no significant interactions.

3.2.1 Optimal Cardiometabolic Risk Score

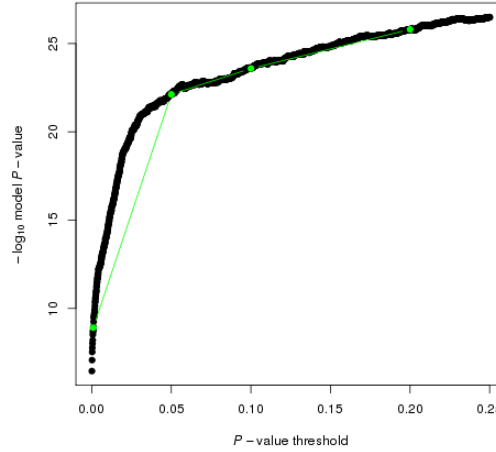
When optimal scores were derived, the thresholds described in Table 3.4 were observed.

Table 3.4: Optimal PRS P value thresholds (T_o) derived for

	LDLc	HDLc	TG	BMI
OHGS_A2	0.0001	0.0055	0.1743	1
OHGS_B2	0.2484	0.0999	0.0002	1
OHGS_C2	0.1299	0.0085	0.1528	1
CCGB_2	0.1807	0.2039	0.004	1

The optimal P value cutoff threshold T_o for BMI was found to be 1 for all cases as demonstrated in 3.2.1. We discuss this result further below, however, for now we exclude BMI from the analysis of optimal risk scores, and opt to use just scores for the lipid traits.

FIGURE 3.3: No optimal P value threshold for BMI.



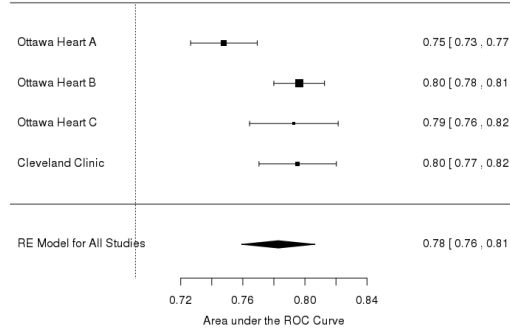
Constructing a logistic regression model, we find that our cumulative score (combining optimal scores from all three traits) is significantly ($P < 2.2 \times 10^{-16}$.) associated with CAD status, and those who have a higher PRS tend to have higher risk for CAD. We detail summary statistics for this association in table 3.5.

Table 3.5: Summary statistics for logistic fit of oPRS.

Study	n_{SNPs}	OR	SE	R^2	AIC	ROC
OHGS_A2	439971	2.2×10^4	1.3×10^3	0.2451	2313	0.7478
OHGS_B2	790128	3.42×10^4	1.5×10^3	0.3377	3061.9	0.7963
OHGS_C2	622050	3.34×10^4	2.5×10^3	0.3009	1095.1	0.7929
CCGB_2	847335	3.78×10^4	2.3×10^3	0.2836	1517.21	0.7953

The oPRS, comprising optimal scores for LDLc, HDLc, and TG predicts CAD with a very high accuracy, explaining between 24.5 and 33.8 percent of variance in CAD. The random effects meta analysis of AUC of the *receiver operator characteristic* (ROC) curve reveals an overall AUC of 0.78[0.75, 0.81], an extremely high value (Figure 3.2.1).

FIGURE 3.4: Random effects meta analysis of oPRS predicting risk for CAD



Though the AUC varies significantly between the cohorts, it is significantly higher than any observed in either the TRS or the CMB scores. However, as noted in table 3.5, each oPRS comprises several hundred thousand SNPs, and it is difficult to assess whether the increase in predictive accuracy is simply a consequence of increasing the number of SNPs used to predict the phenotype, or whether it is a true biological occurrence. When an equal number of SNPs were selected at random in 1000 bootstraps, it was found that the R^2 of our oPRS was not significantly $P > 0.05$ different than that obtained through permutation.

3.2.2 Model Comparisons

When the cardiometabolic $\hat{S}_{CMB;2}$, determined to be the best predictive candidate score for CAD was compared against the TRS score in 1000 random bootstraps in all cohorts combined, it was found to have a significantly larger AUC ($P < 2.2 \times 10^{-16}$). A similar result was found when the oPRS was compared to both the TRS and the CMB scores.

In this thesis we have introduced a novel method for using summary information from co-morbid conditions identified through GWAS for the prediction of complex disease. We validate this technique in a meta analysis of four cohorts.

Previously, polygenic risk scores (PRS) have been used to predict complex diseases and to measure to genetic overlap between conditions. However, often researchers restrict themselves to using the loci which have the highest confidence – those which reach genome-wide significance. Theoretical work disputes this notation, indicating that many low or modest effect variants may be hidden in the region of P -values classically called non-significant. To help better identify candidate variants which may be useful in predicting a condition, we use variants shown to be linked to co-morbid conditions in order to construct a cardiometabolic risk score for coronary artery disease (CAD).

We use meta data from the recent large scale meta-analysis conducted by the CARDIOGRAMC4D consortium to construct the “traditional” PRS for CAD in our four cohorts. The score performs as is expected, significantly predicting CAD with a relatively low explained variance, with NagelKereke’s Pseudo- R^2 averaging 4.7% between the cohorts. This model performs decently at predicting CAD as well, with a meta analyzed overall AUC of the ROC curve of 0.61 with 95% confidence interval between 0.58 and 0.63. Adding biologically relevant covariates increases the predictive accuracy whilst the PRS maintains its significance. Our new model, adding together the PRS from co-morbid conditions as in Section 2.4.2, showed an improvement over the traditional model in all cases. However, the largest (and only statistically significant) difference occurs between the traditional risk score and the score incorporating BMI loci. Interestingly, though the subsequent scores contain

all SNPs present in the second BMI score, the increased noise makes the improvement over the TRS less pronounced. This is directly conflicting with the notion that increasing the number of SNPs used to construct the PRS will usually increase the predictive accuracy, even if it does not increase the significance of the model.

We additionally showed that though our method involves additional SNPs to the PRS, the increase in predictive accuracy occurs that which would be expected by chance, as shown in figure 3.1. This was not the case with the optimal model, as will be described below.

We can only speculate on the true reasons for the observed pattern in PRS association. LDLc, HDLc, and TG are well known risk factors for CAD, and perhaps these results shed some light on the underlying relationship between these phenotypes and CAD. It has been well documented that CAD and BMI share a substantial genetic relationship: in a recent study, the r_G , or genetic correlation, between these two phenotypes was estimated to be $r_G = 0.66$ with standard error 0.2, $P = 5 \times 10^{-4}$. (Cole et al., 2015b) Full results for our cohorts are displayed in table 4.1.

Table 4.1: Genetic Correlations between Obesity and CAD. Adapted from Cole et al. (2015b)

Study	Sample Size	r_G	SE
OHGS_A2	3578	0.566	0.244
OHGS_B2	5718	1.00	0.787
OHGS_C2	2816	0.778	0.713
CCGB_2	4365	0.868	0.496

It is evident that BMI and CAD share substantial genetic pleiotropy. Similar analyses for LDLc, HDLc, and TG have not been conducted. It has recently been demonstrated that adiposity, that is, BMI *per se*, significantly interacted with a PRS for dyslipidemia. (Cole et al., 2014) This adds to a body of evidence suggesting multiple gene by environment interactions may play crucial roles in dyslipidemia risk. Cole et al. (2015a) Thus, it remains an open question whether the genetic predisposition to BMI is interacting with the genetic predisposition to lipids such that the results observed are unexpected.

The combined optimal model was shown to be highly effective at predicting CAD, explaining between 24.5 and 33.8 percent of variance in the phenotype. Recall that estimated heritability h^2 is approximately 40%, meaning that our score explains between 60% and 80% of the variance in CAD attributable to genetics. However, it was found that predictive accuracy explained by the score may be attributable to the number of SNPs which were used in its construction, as the Nagelkerke's Pseudo- R^2 was insignificantly different than 1000 bootstrap permutations using the same number of SNPs. Though it performed well, it is difficult to compare because of this reason.

Additionally, we observed that the optimal solution for BMI was trivial; that is, no P -value threshold $T_o < 1$ was optimal. Referring to Figure 1.4, this may lend evidence to the assertion to

that there is a relatively large number of small effect size SNPs influence BMI rather than a smaller set of large effect size SNPs. This would correspond to a lower π_0 , or proportion of true null SNPs and no maxima < 1 for $P \in [0, 1]$.

Because of this, it is difficult to compare the oPRS to either the TRS or the CMB scores.

4.1 Future Directions

Our study has provided a solid foundation upon which to further elucidate the roll which polygenic risk scores may play in both the prediction and understanding of CAD. Future research may examine the exact algorithm by which the cardiometabolic score is calculated. Specifically, the roll and weighting of duplicated variants must be investigated to see if predictive variants which occur in more than one PRS should be upweighted or prioritized to better facilitate phenotype prediction. Additionally, the roll of variant independence must be examined in depth; currently the optimal score does not include any reservations about variant dependency conditions. Whether or not this has impacted the predictive accuracy remains to be seen.

Additionally, the trends observed must be validated mathematically; we are unsure of the exact mechanics and expected outcomes when scores are combined such as we have done. More research must be done to better understand the benefits and drawbacks of combining information in this way.

In this thesis submitted to partially fulfill the requirements of an honours undergraduate degree in biomedical science, we introduce and validate a novel methodology for combining summary information from GWAS in order to better predict complex disease from co-morbid conditions and phenotypes. We introduce GWAS and their statistical properties, leading into a discussion of PRS. We build upon these definitions to create our new model, which combines scores across several conditions. We find that our new CMB score predicted CAD significantly better than did the TRS. We additionally constructed an optimal PRS (oPRS), which predicted between 60 and 80 % of the variance in CAD attributable to genetics, but was not significantly different from a random bootstrap. We have also shown that the characteristics of oPRS P value threshold selection in BMI are consistent with those observed when a relatively high number of low effect SNPs affect the phenotype, lending evidence to this notion.

Our novel scoring technique represents a significant improvement over the traditional polygenic prediction of CAD. However, much theoretical research is needed to validate and explore the trends observed. We believe that by pushing further into this area of knowledge, eventually PRS, a widely used but often naive methodology, will be improved to the point of clinical utility. Using further iterations of methods like ours, eventually clinicians may be able to predict patient's clinical phenotypes with a high degree of accuracy from a small number of SNPs.

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