USING NETWORK CLUSTERING TO PREDICT COPY NUMBER VARIATIONS ASSOCIATED WITH HEALTH DISPARITIES

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ABSTRACT

Substantial health disparities exist between African Americans and Caucasians in the United States. Copy number variations (CNVs) are one form of human genetic variations that have been linked with complex diseases and often occur at different frequencies among African Americans and Caucasian populations. In this study, we aimed to investigate whether CNVs with differential population frequencies can contribute to health disparities from the perspective of gene networks. We inferred network clusters from two different human gene/protein networks. We then evaluated each network cluster for the occurrences of known pathogenic genes and genes located in CNVs with different population frequencies, and used false discovery rates (FDRs) to rank network clusters. This approach let us identify five clusters enriched with known pathogenic genes and with genes located in CNVs with different frequencies between African Americans and Caucasians. These clustering patterns predict four candidate causal population-specific CNVs that play potential roles in health disparities.
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TABLE OF CONTENTS

ABSTRACT .......................................................................................................................... iii
ACKNOWLEDGEMENTS..................................................................................................... iv
LIST OF TABLES.................................................................................................................. v
LIST OF FIGURES............................................................................................................... vi
LIST OF ABBREVIATIONS ................................................................................................. vii

CHAPTERS

I. INTRODUCTION.............................................................................................................. 1
   1.1 Objectives of the Study ......................................................................................... 1
   1.2 Health Disparities ............................................................................................... 1
   1.3 Genome-Wide Association Studies ................................................................... 4
   1.4 Copy Number Variations .................................................................................... 5
   1.5 Protein-Protein Interaction Networks ............................................................... 6
   1.6 Network-Based Analysis ................................................................................... 8
   1.7 Contributions of the Study ................................................................................ 10

II. MATERIAL AND METHODS........................................................................................ 12
   2.1 Network Clustering ............................................................................................ 13
   2.2 Gene Mapping of CNVs and SNPs .................................................................... 14
   2.3 Cluster Analyses ............................................................................................... 16
   2.4 Biological Significance Analyses ..................................................................... 20

III. RESULTS AND DISCUSSION...................................................................................... 22
   3.1 Network Clustering Results ............................................................................... 22
   3.2 Gene Mapping Results ....................................................................................... 23
   3.3 Cluster Analyses Results ................................................................................... 24
      3.3.1 Clusters enriched with genes located in
            African American CNVs ........................................................................ 30
      3.3.2 Clusters enriched with genes located in Caucasian CNVs................... 31
3.4 Plausible inks of population-specific CNVs in the identified Network Clusters to Health Disparities .............................................. 32
3.4.1 Duplication of \textit{HSPB1} and Health Disparities in African Americans ............................................................... 33
3.4.2 Duplication of \textit{ATP2A1} and Health Disparities in Caucasians .................. 35

IV. CONCLUSION .............................................................................................................................. 36

REFERENCES ........................................................................................................................................ 37

APPENDIX

A. CODES FOR GENE MAPPING OF SNPS AND CNV COORDINATES ............. 44
B. CODES FOR RIGHT-TAILED FISHER’S EXACT TEST .............................. 46
C. CODES FOR FALSE DISCOVERY RATE CALCULATION .............................. 49

VITA ..................................................................................................................................................... 51
LIST OF TABLES

2.1 Contingency table for Fisher’s exact test on pathogenic genes ........................................17
2.2 Contingency table for Fisher’s exact test on CNV genes ..................................................17
3.1 Summary of biological networks ....................................................................................23
3.2 Results of gene mapping of SNPs and CNV coordinates ..................................................24
3.3 Top-ranked clusters from HPRDNet ..................................................................................26
3.4 Top-ranked clusters from MultiNet ....................................................................................27
3.5 Cluster analysis results for HPRDNet and MultiNet ..........................................................28
3.6 Selected genes with potential roles in health disparities and their located CNVs ............29
3.7 Enriched GO terms with CNV-genes in the identified network clusters .........................32
3.8 Associated diseases of genes with enriched GO terms .....................................................33
LIST OF FIGURES

1.1 Death rates of selected ethnicities for five causes of death in the United States........2
2.1 Overview of our approach to identify CNVs associated with health disparities........13
3.1 Graph representations of selected clusters for biological significance analysis........28
3.2 Graph representations of cluster AA1, AA2 and AA3........................................31
LIST OF ABBREVIATIONS

HGV, Human genetic variation
CNV, Copy number variation
SNP, Single nucleotide polymorphism
GWAS, Genome wide association studies
GSA, Gene set analysis
PPIN, Protein-protein interaction network
HPRD, Human protein reference database
PPI, Protein-protein interaction
AA, African American
CA, Caucasian
MCL, Markov Cluster Algorithm
CHD, Coronary Heart Disease
PANOGA, pathway and network oriented GWAS analysis
RA, Rheumatoid Arthritis
FDR, false discovery rate
GO, Gene ontology
OMIM, Online Mendelian Inheritance in Man
dbSNP, Single Nucleotide Polymorphism Database
SERCA1, Sarco/endoplasmic reticulum Ca$^{2+}$-ATPase 1
CHAPTER I
INTRODUCTION

1.1 Objectives of the Study

In this study, we aim to investigate the association of health disparities and genetic variations with different population frequencies, to better understand health disparities between African Americans and Caucasians.

Here, we propose a novel network clustering based approach to associate population-specific copy number variations (CNVs) and health disparities. First, we obtain human gene/protein interaction networks and partition them into gene clusters. Second, we search pathogenic single nucleotide polymorphisms (SNPs) and population-specific CNV loci in genome database to generate gene lists. Third, clusters are ranked based on results of gene enrichment tests for pathogenic genes and CNV-genes. At last, we investigate the biological significance of clusters that were ranked at first place. We will use this approach to identify CNVs that may contribute to health disparities between African Americans and Caucasians in diseases.

1.2 Health Disparities

Health disparities refer to differences in health status between people grouped by social or demographic factors, such as race, gender, income or geographic region. The differences could be in the presence of disease distribution, health outcomes, quality of
health care and access to health care services. In United States, health disparities between African Americans and other racial and ethnic populations are found in life expectancy, death rates, and health measures. Figure 1.1 shows the death rates of selected ethnicities for five causes of death in the United States. The death rates are per 100,000 population and age-adjusted to the 2000 census. AI, AN and PI refer to American Indian, Alaska Native, and Pacific Islander, respectively. As we can see, the death rates of African Americans are found higher than those of other populations in heart diseases, prostate cancer (in male), breast cancer (in female), and diabetes (National Center for Health Statistics 2007; National Center for Health Statistics 2013) (Figure 1.1). According to a recent study, eliminating health disparities would have reduced direct medical care expenditures by about $230 billion and indirect costs associated with illness and premature death by more than $1 trillion for the years 2003 to 2006 (LaVeist et al. 2011).

![Death rates of selected ethnicities in US](image)

Figure 1.1 Death rates of selected ethnicities for five causes of death in the United States.
Many factors contribute to health disparities (American Public Health Association). People with different socioeconomic status, such as income, education and occupation, will have different opinions on health practice and different access to healthy diet. People living in rural area and/or with low income will have trouble to obtain essential health care. People in different culture will have different living style, such as different living habit and diet, which will affect disease prevalence and health treatment outcome.

In addition, human genetic variations (HGVs) play a significant role in health disparities (Fine et al. 2005; Ramos & Rotimi 2009). Human genes contain information that is required to build, regulate and maintain our bodies. HGVs are permanent changes in human genes and may cause alterations in an individual's phenotype, from physical properties to disease risk. According to “out of Africa” model, modern humans speciated in Africa and then migrated to other continents of the world (Stringer & Andrews 1988). During the migration, genetic variations occurred and kept due to random chance, natural selection, and other genetic mechanisms, at different frequencies from region to region (Tishkoff & Verrelli 2003). It is believed that genetic variations are the main reasons of many diseases, and thus different occurrence frequencies can lead to differences in disease susceptibility or resistance among various populations. Studies on associations of genetic variations and diseases are essential to understand disease etiology and health disparities, and are greatly advanced by the completion of the International HapMap Project (Ramos & Rotimi 2009). With the aid of modern genome sequencing techniques, the HapMap contains information of common human genetic variants, such as where
these variants occur in our DNA, and how they are distributed within and among
different population, which can be used by researchers to link genetic variants to diseases.

1.3 Genome-Wide Association Studies

Genome-wide association studies (GWAS) are currently an effective approach to
identify diseases-associated genetic variations (Hirschhorn & Daly 2005; Wang et al.
2005). In GWAS, a group of diseased individuals is compared to a group of healthy
individuals for a large number of Single Nucleotide Polymorphisms (SNPs) (Clarke et al.
2011). The frequency of each allele is compared between two groups and a statistical test
is performed with a null hypothesis that no association exists between disease and the
SNP. Usually tests of millions of SNPs are carried out, which requires multiple
hypothesis testing procedures to control false positives (Dudbridge & Gusnanto 2008).
Although GWAS have revealed many disease-associated SNPs, only a few of them are
associated with moderate or large increase in disease risk, and some well-known genetic
risk factors have been missed (Williams et al. 2007). One possible reason is that GWAS
focus only on individual genetic variations and do not address complex gene interactions
(Moore & Williams 2009). Another possible reason is that the current statistical analysis
is “unbiased”, since it ignores available knowledge of disease pathobiology (Moore et al.
2010).

Several approaches tried to incorporate GWAS results with known biological
knowledge. One of them is called Gene Set Analysis (GSA) (Cantor et al. 2010; Lehne et
al. 2011; Wang et al. 2007), which associates variations in an entire set of genes with a
phenotype. A gene set is defined as a set of genes that are involved in common biological
processes or pathways, or as a set of interacting proteins identified from protein-protein interaction networks (Lehne et al. 2011). In GSA, enrichment tests are performed by comparing the frequency of significantly associated SNPs in a particular set of genes with that among all other genes not in the set. Gene sets containing significantly more associated SNPs will have closer association with the corresponding phenotypes. The advantage of GSA is that it detects associations of the phenotype with a gene set, not individual SNPs. Therefore it does not ignore SNPs that have low \( p \)-values but still contribute to phenotypes, and it reduces the number of statistical tests and requires less stringent multiple testing correction (Lehne et al. 2011).

### 1.4 Copy Number Variations

Unlike SNPs, which affect only one single nucleotide base, copy number variations (CNVs) are duplications or deletions of relatively large genomic segments that can contain one or more genes (Feuk et al. 2006; Freeman et al. 2006). The widespread presence of CNVs in normal individuals was first reported in 2004 (Iafrate et al. 2004; Sebat et al. 2004). And to date, over 100,000 non-overlapping human CNVs have been identified, with the size varying from 50 base pair to more than one million bases pairs, and they cover about 70% of the whole genome (MacDonald et al. 2014).

In early genetic association studies, CNVs have been associated with various complex diseases (Feuk et al. 2006; Ionita-Laza et al. 2009). Updates on CNVs’ roles in some diseases, such as psychoses (Lee et al. 2012), autism (Wang et al. 2013), autoimmunity (Olsson & Holmdahl 2012) and schizophrenia (Hosak et al. 2012), have been reviewed recently. Computational tools and methods have been developed to help
address the potential roles of CNVs in human diseases. The CNVannotator was
developed to provide considerable capabilities for researchers to annotate specific CNVs
in a reliable and efficient manner (Zhao & Zhao 2013). The NETBAG+ algorithm was
developed to search for strongly cohesive gene clusters affected by CNVs, using a
likelihood network constructed based on a combination of various functional descriptors.
(Gilman et al. 2012). Recently, it is reported that CNVs can occur at different frequencies
between African Americans and Caucasians (McElroy et al. 2009), and naturally the
question about the potential roles of CNVs in health disparity is raised.

1.5 Protein-Protein Interaction Networks

Protein-protein interactions (PPIs) play diverse roles in biology. It is observed that
proteins seldom carry out their function in isolation, and usually proteins involved in the
same cellular processes interact with each other (von Mering et al. 2002). Advanced
high-throughput technologies, such as yeast-two-hybrid screening, mass spectrometry,
and protein microarray chip technologies, have generated huge data sets of protein-
protein interactions (von Mering et al. 2002).

Several databases have been constructed as repositories for experimentally
discovered protein interactions (Mathivanan et al. 2006). PPIs are incorporated into PPI
databases through curation from the literatures by biologists, or through direct deposit by
the investigators before their publication. For example, Human Protein Reference
Database (HPRD) is a joint project between the Institute of Bioinformatics in Bangalore,
India and the Pandey lab at Johns Hopkins University in Baltimore, USA. HPRD
contains annotations related to human proteins based on experimental evidence from the
Protein-protein interaction (PPI) data can be represented in the form of networks, in which nodes are proteins and edges are interactions. The protein-protein interaction network (PPIN) can help understand the basic scheme of cell functions by correlating the components of the network with their cellular functions, which can be done by clustering processes (Lin et al. 2007; Pizzuti et al. 2012; Wang et al. 2010). In PPIN, a cluster is a set of genes that share a large number of interactions, and the clustering process is to group genes into clusters which contain more interactions among genes in the same cluster than in different clusters. Clustering process can identify both protein complexes and functional modules (Lin et al. 2007; Pizzuti et al. 2012; Wang et al. 2010). Protein complexes are groups of proteins that bind to each other at the same time and place, while functional modules consist of proteins that participate in the same cellular process through interactions between themselves at a different time and place. Usually the PPINs do not contain information about when and where proteins interacts, therefore protein
complexes and functional modules are not treated differently in clustering processes. The results of clustering process of PPINs can help to infer the principal function of each cluster from the functions of its members, and suggest possible functions of cluster members based on the functions of other members.

Many distance-based or graph-based clustering algorithms were developed to cluster PPINs (Lin et al. 2007; Pizzuti et al. 2012; Wang et al. 2010). The Markov Clustering (MCL) algorithm is a fast, scalable, and unsupervised clustering algorithm, which simulates stochastic flows in graphs (van Dongen 2000). The algorithm simulates random flows within a graph by alternation of two operations called expansion and inflation. In expansion, the flow moves within the same dense regions or out to other dense regions. The inflation operation strengthens the flow within the dense regions and weakens the flow out of the dense regions. The expansion and inflation steps are repeated until a steady state is reached. A recent study compared MCL with other three clustering algorithms, restricted neighborhood search clustering (RNSC), super paramagnetic clustering (SPC) and molecular complex detection (MCODE), on six PPINs to detect previously annotated gene clusters (Brohee & van Helden 2006). The conclusion was that MCL algorithm outperformed the other algorithms in the extraction of complexes from interaction networks.

1.6 Network-Based Analysis

Gene/Protein interaction networks combined with GWAS data can help understand complex biological activities and cellular mechanisms of complex diseases (Barabasi et al. 2011; Halldorsson & Sharan 2013; Sharan et al. 2007; Vidal et al. 2011;
Wang et al. 2011). This is based on the assumption of “guilt by association”, which means that genes associated with the same or related functions or diseases tend to interact with each other and cluster together with high connectivity in networks (Altshuler et al. 2000; Oliver 2000).

One example of using PPIN to identify disease-associated genes was reported in a study of incident Coronary Heart Disease (CHD) (Jensen et al. 2011). In this study, an experiment-derived PPI database InWeb was used to produce unbiased protein complexes and corresponding gene sets, which were then ranked based on results of enrichment tests of CHD-associated genes. In the identified gene set, five out of 19 genes were involved in abnormal cardiovascular system physiological features, and pathways related to blood pressure regulation were significantly enriched.

Another methodology that utilizes the PPINs to discover disease associated clusters is called the pathway and network oriented GWAS analysis (PANOGA), which combines GWAS data with current knowledge of biochemical pathways, PPINs, and functional and genetic information of selected SNPs (Bakir-Gungor & Sezerman 2011). In their study, genes related to significant SNPs from GWAS data were identified and were assigned with functional attributes, which were used in the process of identifying clusters associated with the disease. Then, genes in one identified cluster were tested whether they are part of important pathways. The application of this methodology on Rheumatoid Arthritis (RA) dataset identified new RA-associated pathways, in addition to pathways previously identified by GWAS analysis. The newly identified pathways were found to include many genes that are known to be used as drug targets for the treatment of RA. Moreover, new genes have been identified to be associated with RA.
Protein interactions could provide important clues to help illustrate SNP’s functional association (Huang et al. 2010). Protein interaction network was combined with other traditional hybrid features, such as sequence, structure and pathway properties, and it was used to establish predictors using hundreds of those features. These predictors can correctly identify around 80% of known disease-associated SNPs and is valuable to predict undiscovered disease-associated SNPs.

In another approach, a genome-scale functional gene network, named HumanNet, was constructed by incorporating gene expression, protein interaction, sequence and other genomic data to prioritize candidate disease genes, which can facilitate both seed gene-based and GWAS-based disease association studies (Lee et al. 2011). In seed gene-based approach, gene connections in the network were assigned with weights, calculated by using label propagation algorithms based on their distance to the seed genes. Genes connected to seed genes with larger weights were be considered as more likely to be associated with target diseases. Although for GWAS data there are no definite seed genes, this approach can still boost the power of association analysis by using a different ranking score (Lee et al. 2011). In the analysis of Crohn’s disease and type 2 diabetes, the HumanNet not only boosted the identification of correct associations, but organized the associated genes into processes, which arouse attentions to genes that were not significantly identified in GWAS.

1.7 Contributions of the Study

Although genetic factors play a crucial role in health disparities, only a few association studies have been reported in common complex diseases, such as breast
cancer (Long et al. 2013), prostate cancer (Bensen et al. 2014; Bensen et al. 2013; Xu et al. 2011), type 2 diabetes (Ng et al. 2014) and vascular diseases (Wei et al. 2011). In order to better understand health disparities between African Americans and Caucasians, we aim to investigate the association of health disparities and genetic variations with different population frequencies.

Here, we propose a novel network clustering based approach on CNVs for health disparities. First, we choose to focus on CNVs. Although CNVs are one important type of genetic variations, and can occur at different frequencies among African Americans and Caucasians, no association studies have been reported so far to our best knowledge. Therefore, this work is the first study on association of CNVs and health disparities.

Second, our approach is on gene level, and pathogenic SNPs and population specific CNV loci are mapped to corresponding gene names. Current GWAS on health disparities still focused on individual SNPs, but we choose to focus on genes, because only a small fraction of the genetic heredity of most diseases can be explained by the SNPs, and a gene-based approach can allow us using the information encoded by protein interaction networks (Lee et al. 2011). Third, association analysis in our approach uses gene clusters inferred from gene networks, which is based on the rationale that interacting genes often have the same functions or participate in the same biological processes. In addition, unlike common Gene Set Analysis (GSA) studies that compares significantly associated SNPs (Cantor et al. 2010; Lehne et al. 2011; Wang et al. 2007), our novel approach compares the frequency of pathogenic genes or population specific CNV related genes between clusters to evaluated the relationship between clusters and diseases or CNVs.
CHAPTER II
MATERIALS AND METHODS

This chapter introduces materials (gene/protein networks and gene sets) we collected and prepared for this study, and methods we used in clustering process, cluster analyses and biological significance analysis.

Our overall work flow is shown in Figure 2.1. To identify potential CNVs associated with health disparities, our basic idea is to identify gene clusters that are enriched with both pathogenic genes and genes located in population-specific CNVs. Health disparities in diseases associated with identified clusters could be considered as results of the occurrence of corresponding CNVs. Specifically, we first obtained two human gene/protein networks and partitioned them into gene clusters. We then identify disease-associated genes and genes located in population-specific CNVs in those clusters. Statistical tests were performed on each cluster to estimate its significances of containing pathogenic genes and genes in population-specific CNVs. Finally, we ranked gene clusters based on false discovery rates (FDRs). Top-ranked clusters were enriched both for pathogenic genes and for genes in CNVs with differential frequencies between African-Americans and Caucasians. These clusters were then searched for enriched Gene Ontology (GO) terms and related disease phenotypes to identify corresponding biological significance.
2.1 Network Clustering

We obtained two human gene/protein networks, one from Human Protein Reference Database (HPRD) (Mishra et al. 2006; Peri et al. 2003; Prasad et al. 2009) and another from MultiNet (Khurana et al. 2013). The HPRD network (referred to as HPRDNet) is one of the largest human gene/protein interaction networks, and contains only physical protein-protein interactions (PPIs). The MultiNet is a unified network including PPI, phosphorylation, metabolic, signaling, genetic and regulatory networks. These two networks share 8468 genes (89.6% of HPRDNet and 58.6% of MultiNet) but only 8769 interactions (23.8% of HPRDNet and 8% of MultiNet). These two networks were both partitioned into gene clusters using the Markov Cluster (MCL) Algorithm (van
Dongen 2000). MCL (version10-201) was installed and run in an Ubuntu 11.10 system. The following command was used to run clustering:

```
mcl <network> --abc -I <I value> --force-connected=y -o <result>
```

Option `<network>` refers to the input file that contains the gene/protein interaction network. In the input file, each line contains a pair of gene names, separated by a tab space, which represent a gene-gene interaction. Option `<I value>` refers to the inflation parameter I, which was from 1.1 to 2.0 with a step of 0.1. Option `<result>` refers to the output file to which the clustering results will be saved. In the output file, each line contains a set of gene names separated by a tab space, which are member of a cluster.

### 2.2 Gene Mapping of CNVs and SNPs

Two sets of genes were used in this study: genes located in population-specific CNVs and pathogenic genes. Currently, there are no ready-made sources containing information of these genes. However, coordinates of disease-associated SNPs and population-specific CNVs were available and were searched in the UCSC Genome Database (Karolchik et al. 2014) through its MySQL API to obtain the corresponding gene name sets. All works were done using codes in Java. The following Java statements were used to establish the connection to UCSC Genome Database MySQL interface:

```java
// setup connection to UCSC Genome Database
String username = "genome";
String password = "";
String url = "jdbc:mysql://genome-mysql.cse.ucsc.edu/hg19";
Class.forName("com.mysql.jdbc.Driver");
Connection con = DriverManager.getConnection(url, username, password);
```
CNV coordinates were obtained from a CNV map in African Americans and Caucasians (McElroy et al. 2009). There are three types of CNVs in this map: (1) CNVs only occur in African Americans, (2) CNVs only occur in Caucasians, and (3) CNVs occurred in both African Americans and Caucasians. To simplify the analysis, we further partitioned the last type: CNVs that occurred more than 50% in African Americans or in Caucasians were combined with the first and second types of CNVs, respectively. This repartition resulted in two modified CNV sets with differential population frequencies. The coordinates of these CNVs were then searched in the UCSC Genome Database through its MySQL API to obtain the corresponding gene sets. The SQL statements were formed in Java codes (APPENDIX A) and submitted, in which begin, end, and chrom refer to the starting positions, ending positions and chromosomes of the CNVs, respectively:

```sql
// search related genes of CNVs
SELECT DISTINCT X.geneSymbol, G.chrom, G.txStart, G.txEnd
FROM knownGene as G, kgXref as X
WHERE ((G.txStart>begin AND G.txEnd<end) OR
(G.txStart>begin AND G.txStart<end) OR
(G.txEnd>begin AND G.txEnd<end) OR
(G.txStart<begin AND G.txEnd>end) AND
X.kgId = G.name AND G.chrom = chrom);
```

For simplicity, CNVs that occur more frequently in African Americans were called African-American CNVs or CNV_AA; CNVs that occur more frequently in Caucasians were called Caucasian CNVs or CNV_CA.

Disease-associated SNPs were retrieved from a file, OimimVarLocusIdSNP.bcp, obtained from the FTP site of Single Nucleotide Polymorphism Database (dbSNP) (Sherry et al. 2001). Coordinates of these SNPs were then queried against the MySQL
API of the UCSC Genome Database to identify genes in which those SNPs are located.

The following SQL statements were composed in Java codes (see APPENDIX A) and submitted, in which SNP refers to the RSid of the SNPs:

```sql
//search related genes of SNPs.
select distinct S.name, X.geneSymbol
from snp138 as S, knownGene as G, kgXref as X
where S.name = SNP
AND
X.kgId = G.name AND S.chrom = G.chrom AND
G.txStart <= S.chromStart AND G.txEnd >= S.chromEnd;
```

This identified gene set was termed as pathogenic genes.

### 2.3 Cluster Analyses

Clusters were obtained from both HPRDNet and MultiNet using MCL with a range of ten inflation parameters. For each cluster, contingency tables were constructed using the numbers of pathogenic genes and population-specific CNV-related genes. Table 2.1 is for pathogenic significance test, and Table 2.2 is for tests of enrichment significance of CNV-related genes (CNV_AA or CNV_CA genes). Q and q are the number of pathogenic genes in the whole networks and that in current cluster, respectively. N and m are the number of genes in whole networks and that in current cluster, respectively. S and s are the number of CNV_AA or CNV_CA genes in the whole networks and that in current cluster, respectively.

In statistics, a contingency table is a type of table that displays the frequency distribution of multiple variables, usually in a two by two format. The significance of the difference between the two proportions (derived based on observed frequencies) can be evaluated by various statistical tests, such as Pearson's chi-squared test and Fisher's exact
test. If the proportions in the different columns are significantly different between rows (or vice versa), we say that there is a contingency between the two variables. In our case, we want to know whether a cluster contains more pathogenic genes or population-specific CNV-related genes than all of the other clusters. If it does, we say this cluster is enriched with such genes and thus has stronger connections to diseases or is more likely to be affected by population-specific CNVs. If a cluster is found to be significant in both enrichment tests, it will be of most interest to us.

Table 2.1
Contingency table for Fisher’s exact test on pathogenic genes

<table>
<thead>
<tr>
<th>Genes in this cluster</th>
<th>Pathogenic Genes</th>
<th>Non-pathogenic Genes</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genes in other clusters</td>
<td>$q$</td>
<td>$m-q$</td>
<td>$m$</td>
</tr>
<tr>
<td></td>
<td>$Q-q$</td>
<td>$N-Q-m+q$</td>
<td>$N-m$</td>
</tr>
<tr>
<td>Total</td>
<td>$Q$</td>
<td>$N-Q$</td>
<td>$N$</td>
</tr>
</tbody>
</table>

Table 2.2
Contingency table for Fisher’s exact test on CNV genes

<table>
<thead>
<tr>
<th>Genes in this cluster</th>
<th>CNV Genes</th>
<th>Non-CNV Genes</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genes in other clusters</td>
<td>$s$</td>
<td>$m-s$</td>
<td>$m$</td>
</tr>
<tr>
<td></td>
<td>$S-s$</td>
<td>$N-S-m+s$</td>
<td>$N-m$</td>
</tr>
<tr>
<td>Total</td>
<td>$S$</td>
<td>$N-S$</td>
<td>$N$</td>
</tr>
</tbody>
</table>

In this study, right-tailed Fisher’s exact tests were applied to these contingency tables to calculate enrichment significance of pathogenic genes, CNV_AA or CNV_CA genes, respectively. Fisher's exact test is a statistical test used in the analysis of
contingency tables. It is valid for all sample sizes, but in practice it is employed mostly when sample sizes are small, which is the main reason it is chosen in for our analyses. Using Table 2.1 as an example, the null hypothesis $H_0$ is that the proportion of pathogenic genes in one cluster less than or equals to that in all other clusters, and the alternative hypothesis $H_1$ indicates that this pathogenic occurrence in this cluster is more than random expectation:

$$H_0: \frac{q}{m} \leq \frac{Q - q}{N - m}$$

$$H_1: \frac{q}{m} > \frac{Q - q}{N - m}$$

in which $Q$ and $q$ are the number of pathogenic genes in the whole networks and that in current cluster, respectively, and $N$ and $m$ are the number of genes in whole networks and that in current cluster, respectively. In other words, if the null hypothesis is true, we would have

$$q \leq \frac{Q}{N} \times m$$

The question we ask is: what is the probability that the observed $q$ value is larger than the expected value in the null hypothesis? The right-tailed Fisher’s exact test will give the answer: if the $p$-value is small (common cutoff values are 0.001, 0.01, 0.05, or 0.10), we can say that in this cluster pathogenic genes were significantly enriched. The smaller the $p$-values, the more significant the enrichment is. The right-tailed Fisher’s exact tests were performed in the R statistical environment (R Development Core Team 2013), with the following R statements composed in Java codes (see APPENDIX B) and submitted to the R engine:
The right-tailed Fisher’s exact tests were performed to each cluster in each clustering results, which led to the multiple comparisons problem. The multiple comparisons problem, or multiple testing problem, occurs when a set of statistical tests are performed simultaneously (Miller 1981), in which the null hypothesis are more likely to be incorrectly rejected based on individual tests when all tests were considered as a whole. The False discovery rate (FDR) control is a statistical method to correct for multiple comparisons. In a list of tests, FDR procedures are designed to control the proportion of incorrectly rejected null hypotheses, i.e. “false discoveries” (Benjamini & Hochberg 1995). There are many statistical procedures that use \( p \)-values to estimate or control the FDR, such as Benjamini-Hochberg procedure (Benjamini & Hochberg 1995) and Q-value procedure (Storey et al. 2004). However, most of them assume that \( p \)-values are continuously distributed and based on two-sided tests. Therefore, it is difficult to reliably estimate the FDR when the \( p \)-values are discrete or based on one-sided tests. Since \( p \)-values in our study are discrete and based on one-sided tests, a proper FDR calculation procedure needs to be carefully chosen. The Robust FDR Routine does not rely on the assumptions that tests are two-sided or yield continuously \( p \)-values, and was shown to have excellent performance in a series of data (Pounds & Cheng 2006). Based
on obtained \(p\)-values from the right-tailed Fisher’s exact tests, we calculated FDRs using the Robust FDR Routine in the R statistical environment. The following R statements were composed in Java codes (see APPENDIX C) and submitted to the R engine:

```r
// Run robust FDR routine.
// p is the vector of all sorted p-values.
robust.fdr(p, discrete=T, use8=F)$fdr;
```

Ranking were applied to clusters with \(p\)-value\(<0.10\) and FDR\(<0.20\) in both enrichment tests for pathogenic genes and population-preferred CNVs genes. Assuming both tests are independent, the FDR values were multiplied and the products were used to rank the network clusters.

The same cluster analysis procedure was applied to each clustering results with different MCL inflation parameters. For clarity, we focused our biological significance analyses on clusters that were consistently ranked at the first place with different MCL inflation parameter values.

### 2.4 Biological Significance Analyses

To understand the biological significance of the clusters, their corresponding Gene Ontology (GO) terms were analyzed. Gene ontology is a project to unify the representation of gene and gene product attributes (Gene Ontology Consortium 2008). More specifically, the project aims to develop and maintain the vocabulary of gene and gene product attributes, annotate genes and gene products, and provide tools for data access and functional interpretation. GO terms describe properties of genes and their products and are grouped into three domains: cellular component (where they locate), molecular function (what they do at the molecular level), and biological process (which
molecular events they participate). One of the main uses of the GO terms is to perform enrichment analysis on gene sets by comparing one target gene set to the background gene set. If a GO term appears more often in the target gene set than in the background gene set, it is said to be enriched in this gene set, or this gene set is highly related to this GO term, which could help to understand the underlying biological relevance.

In this study, biological relevance of selected network clusters were analyzed by the Gene Ontology enrichment analysis and visualization tool, or GOrilla (Eden et al. 2009) to search for enriched GO terms. In GOrilla search, genes in the selected clusters were target genes, and all other genes in the network were treated as background genes. To investigate the possible links of population-specific CNVs to health disparities, we first identified significantly enriched GO terms that are associated with CNV_AA or CNV_CA genes. We then focused on the pathogenic genes associated with the enriched GO terms, and examined their related disease phenotypes in OMIM database (Online Mendelian Inheritance in Man 2014). These disease phenotypes were searched for reported health disparities between African American and Caucasian populations.
CHAPTER III
RESULTS AND DISCUSSION

This chapter shows our results in network clustering, gene mapping and cluster analyses, and discusses the plausible links of population-specific CNVs in the identified network clusters to health disparities.

3.1 Network Clustering Results

Two gene/protein interaction networks were chosen in this study: HPRDNet and MultiNet. For HPRDNet, three types of interactions were removed before clustering process: 1) interaction between same gene; 2) interaction involving unknown genes; 3) and interactions with ambiguous genes. For MultiNet, all interactions were submitted to clustering process. Clusters were inferred using MCL with ten different inflation values. Descriptive statistics of the two networks and their clustering results are summarized in Table 3.1. When inflation parameter I was increased, the cluster sizes decreased and the cluster numbers increased. This is because higher I value increases the granularity or tightness of clusters. The “--force-connected=” option is also proven to have an effect on clustering results for both networks. When this option was set to “N”, we identified several uninformative clusters with some genes do not connect to any other genes in the same cluster.
Table 3.1

Summary of biological networks

<table>
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<tr>
<th>Network</th>
<th>Inflation Value</th>
<th>Total Clusters</th>
<th>Cluster Sizes</th>
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</thead>
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<td></td>
<td></td>
<td></td>
<td>Maximum</td>
</tr>
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<td>HPRDNet:</td>
<td>1.1 9451 genes</td>
<td>111</td>
<td>9203</td>
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<tr>
<td></td>
<td>1.2</td>
<td>128</td>
<td>9025</td>
</tr>
<tr>
<td></td>
<td>1.3 36880 interactions</td>
<td>363</td>
<td>3454</td>
</tr>
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<td>660</td>
<td>432</td>
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<td></td>
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<td>260</td>
</tr>
<tr>
<td></td>
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<td>192</td>
</tr>
<tr>
<td></td>
<td>1.7 1.1</td>
<td>1704</td>
<td>152</td>
</tr>
<tr>
<td></td>
<td>1.8 1.1</td>
<td>1990</td>
<td>146</td>
</tr>
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<td></td>
<td>1.9 1.1</td>
<td>2222</td>
<td>119</td>
</tr>
<tr>
<td></td>
<td>2.0 1.1</td>
<td>2447</td>
<td>90</td>
</tr>
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<td>MultiNet:</td>
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<td>14399</td>
</tr>
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<td>2.0 1.1</td>
<td>2116</td>
<td>804</td>
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</table>

3.2 Gene Mapping Results

Chromosome coordinates of pathogenic SNPs and population-specific CNVs were searched in the UCSC Genome Database. Totally 2810 pathogenic genes, 194 CNV_AA genes and 258 CNV_CA genes were obtained. Since this study focuses on network-derived gene clusters, only genes that are listed in HPRDNet or MultiNet were kept. Details of gene mapping results are shown in Table 3.2.
Table 3.2
Results of gene mapping of SNPs and CNV coordinates

<table>
<thead>
<tr>
<th></th>
<th>Pathogenic Genes</th>
<th>CNV_AA</th>
<th>CNV_CA</th>
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</thead>
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<tr>
<td>Total in HPRDNet</td>
<td>2810</td>
<td>194</td>
<td>258</td>
</tr>
<tr>
<td>in MultiNet</td>
<td>1791</td>
<td>48</td>
<td>62</td>
</tr>
</tbody>
</table>

3.3 Cluster Analysis Results

We performed cluster analyses on each of the ten clustering results for both HPRDNet and MultiNet. Ranking were applied only to clusters with $p$-value<$0.10$ and FDR<$0.20$ in both enrichment tests for pathogenic genes and those for population-preferred CNVs genes. The products of FDRs of both enrichment tests were used to rank the network clusters.

The ranking results are listed in Table 3.3 and Table 3.4. The value of inflation parameter I used in clustering process is from 1.1 to 2.0, increased by 0.1. Cluster NO is the serial number of a cluster. CNV_AA and CNV_CA are CNV-related genes. Cluster Names are names of clusters selected for biological significance analyses. $p$_CNV and FDR_CNV, and $p$_OMIM and FDR_OMIM are $p$-values and FDR values from enrichment tests for CNV-related genes and pathogenic genes, respectively. FDR product is the multiplication result of FDR_CNV and FDR_OMIM and is used for ranking.

We focused on clusters that were consistently ranked at the first place with different MCL inflation parameter values for further biological significance analyses. It is worth to mention that clusters containing gene $CYP2E1$ were filtered out, although in
HPRDNet these clusters have been ranked three times at first place in cluster ranking for CNV_AA gene enrichment tests, and three times at first place for CNV_CA gene enrichment tests (Table 3.3). This is because gene CYP2E1 is affected by multiple CNVs and these CNVs have different population preferences. CYP2E1’s location was compared with those CNVs’ loci. It is found that CYP2E1 is located in the overlapped region among those CNVs, which means it may not have CNV-caused population-preferred variations, and may not contribute to health disparities. Therefore, clusters containing gene CYP2E1 were not included in the following analysis, and the corresponding clusters ranked at second place were selected instead.

Details of selected clusters are listed in Table 3.5, and their graph representations are shown in Figure 3.1. In Figure 3.1, each rounded rectangle represents a gene and each gray line represents a gene-gene interaction. Black rounded rectangles represent non-pathogenic genes and orange rounded rectangles represent pathogenic genes. Genes labeled with red or blue ovals are located in African American CNVs or in Caucasian CNVs. Genes with Green lines share the same GO terms. In each cluster, different line types represent the enrichment of different GO terms. Line types shown in different clusters refer to the enrichment of different GO terms. The CNV_AA or CNV_CA genes in the selected clusters and the details of their corresponding CNVs are listed in Table 3.6. In Table 3.6, Chr represents chromosomes. CNV Regions are regions of CNVs identified in more than a single individual. All CNVs listed have a type of Duplication, referring to one copy increase. CNV Regions and Types are from the CNV map (McElroy et al. 2009). CNV Occurrence describes in CNVs occurrence in African American and Caucasian populations.
Table 3.3
Top-ranked clusters from HPRDNet

<table>
<thead>
<tr>
<th>I</th>
<th>Cluster No</th>
<th>Cluster Name</th>
<th>CNV_AA</th>
<th>CNV_CA</th>
<th>OMIM</th>
<th>Size</th>
<th>p_CNV</th>
<th>FDR_CNV</th>
<th>p_OMIM</th>
<th>FDR_OMIM</th>
<th>FDR product</th>
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<td>-</td>
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<td>-</td>
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<td>11</td>
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Table 3.4

Top-ranked clusters from MultiNet

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<th>I</th>
<th>Cluster No.</th>
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<th>CNV_AA</th>
<th>CNV_CA</th>
<th>OMIM</th>
<th>Size</th>
<th>p_CNV</th>
<th>FDR_CNV</th>
<th>p_OMIM</th>
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<tr>
<td>351</td>
<td>CA1</td>
<td>ATP2A1</td>
<td>4</td>
<td>5</td>
<td>0.0331</td>
<td>0.1814</td>
<td>0.0021</td>
<td>0.0467</td>
<td>8.47E-03</td>
<td></td>
<td></td>
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<tr>
<td>1.8</td>
<td>377</td>
<td>AA4</td>
<td>HSPB1</td>
<td>-</td>
<td>5</td>
<td>5</td>
<td>0.0220</td>
<td>0.0809</td>
<td>7.16E-5</td>
<td>0.0067</td>
<td>5.42E-04</td>
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<tr>
<td>412</td>
<td>CA1</td>
<td>ATP2A1</td>
<td>4</td>
<td>5</td>
<td>0.0331</td>
<td>0.1347</td>
<td>0.0021</td>
<td>0.0509</td>
<td>6.86E-03</td>
<td></td>
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<tr>
<td>248</td>
<td>-</td>
<td>CLN3</td>
<td>4</td>
<td>7</td>
<td>0.0461</td>
<td>0.1459</td>
<td>0.0116</td>
<td>0.1625</td>
<td>2.37E-02</td>
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<td></td>
</tr>
<tr>
<td>1.9</td>
<td>410</td>
<td>AA4</td>
<td>HSPB1</td>
<td>-</td>
<td>5</td>
<td>5</td>
<td>0.0220</td>
<td>0.0747</td>
<td>7.16E-5</td>
<td>0.0078</td>
<td>5.38E-04</td>
</tr>
<tr>
<td>443</td>
<td>CA1</td>
<td>ATP2A1</td>
<td>4</td>
<td>5</td>
<td>0.0331</td>
<td>0.1159</td>
<td>0.0021</td>
<td>0.0663</td>
<td>7.68E-03</td>
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<td></td>
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<tr>
<td>316</td>
<td>-</td>
<td>CLN3</td>
<td>4</td>
<td>6</td>
<td>0.0396</td>
<td>0.1190</td>
<td>0.0056</td>
<td>0.1118</td>
<td>1.33E-02</td>
<td></td>
<td></td>
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<tr>
<td>2.0</td>
<td>142</td>
<td>ECHS1</td>
<td>-</td>
<td>8</td>
<td>12</td>
<td>0.0519</td>
<td>0.1196</td>
<td>6.55E-5</td>
<td>0.0096</td>
<td>1.15E-03</td>
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<tr>
<td>479</td>
<td>CA1</td>
<td>ATP2A1</td>
<td>4</td>
<td>5</td>
<td>0.0331</td>
<td>0.0988</td>
<td>0.0021</td>
<td>0.0728</td>
<td>7.19E-03</td>
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</table>
Table 3.5
Cluster analysis results for HPRDNet and MultiNet

<table>
<thead>
<tr>
<th>Network</th>
<th>Cluster Name</th>
<th>CNV_AA</th>
<th>CNV_CA</th>
<th>Pathogenic gene number</th>
<th>Cluster Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPRDNet</td>
<td>AA1</td>
<td>HSPB1</td>
<td>-</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>AA2</td>
<td>HSPB1</td>
<td>-</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>AA3</td>
<td>HSPB1</td>
<td>-</td>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>CA1</td>
<td>-</td>
<td>ATP2A1</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>MultiNet</td>
<td>AA4</td>
<td>HSPB1</td>
<td>-</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>CA1</td>
<td>-</td>
<td>ATP2A1</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 3.1 Graph representations of selected clusters for biological significance analysis
Table 3.6

Selected genes with potential roles in health disparities and their located CNVs

<table>
<thead>
<tr>
<th>Gene</th>
<th>Chr</th>
<th>Gene Coordinates</th>
<th>CNV Region</th>
<th>CNV Type</th>
<th>CNV Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSPB1</td>
<td>7</td>
<td>75,931,861-75,933,614</td>
<td>75,867,431-76,481,102</td>
<td>Duplication</td>
<td>Only in African American</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>75,929,740-76,481,102</td>
<td>Duplication</td>
<td>Only in African American</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>75,929,740-76,568,388</td>
<td>Duplication</td>
<td>higher in African American than in Caucasian</td>
</tr>
</tbody>
</table>
3.3.1 Clusters enriched with genes located in African American CNVs

We found four similar clusters, (AA1, AA2, and AA3 in HPRDNet and AA4 in MultiNet), that are enriched both for pathogenic genes and for genes located in African-American CNVs (Table 3.5). In HPRDNet, cluster AA1, AA2 and AA3 together were ranked at first place five times; and cluster AA4 were ranked at first place five times in MultiNet (Table 3.4). Cluster AA1 contains 11 genes, within which eight are pathogenic genes (Figure 3.1A). Cluster AA2 and AA3 contain one and two more genes than cluster AA1, respectively (Figure 3.2). In MultiNet, cluster AA4 contains five genes and can be considered as a sub-cluster of cluster AA1, AA2 and AA3 (Figure 3.1B). All four clusters contain gene \textit{HSPB1} (Table 3.5), which is mainly duplicated in African Americans (Table 3.6). Since cluster AA1, AA2 and AA3 were selected from the same network and are highly similar to each other, only cluster AA1 and AA4 were studied in biological significance analyses.
3.3.2 Clusters enriched with genes located in Caucasian CNVs

In both HPRDNet and MultiNet, the same cluster, named as CA1, was identified to be enriched with both pathogenic genes and genes located in Caucasian CNVs (Table 3.5). Cluster CA1 was ranked at first place four times in HPRDNet (Table 3.3) and seven times in MultiNet (Table 3.4). This cluster contains five genes, and four of them are associated with diseases (Figure 3.1C). Cluster CA1 contains gene *ATP2A1* which is duplicated only in Caucasians (Table 3.6).
3.4 Plausible Links of population-specific CNVs in the identified Network Clusters to Health Disparities

To investigate the possible links of population-specific CNVs to health disparities, we first identified significantly enriched GO terms that are associated with CNV_AA or CNV_CA genes in the identified network clusters. We then focus on the pathogenic genes with the enriched GO terms, and examined their associated disease phenotypes in OMIM database. The results of GO term enrichment analysis are listed in Table 3.7, and the associated diseases are listed in Table 3.8.

<table>
<thead>
<tr>
<th>Clusters</th>
<th>Involved Genes</th>
<th>GO Domain</th>
<th>GO ID</th>
<th>GO term</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA1</td>
<td><em>HSPB1, CRYAA, CRYAB, CRYBB2, CRYBA1, CRYBA2</em></td>
<td>Molecular Function</td>
<td>GO:0042802</td>
<td>Identical protein binding</td>
</tr>
<tr>
<td>AA4</td>
<td><em>HSPB1, CRYAA, CRYAB</em></td>
<td>Biological Process</td>
<td>GO:0043086</td>
<td>negative regulation of catalytic activity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>negative regulation of apoptotic process</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>negative regulation of programmed cell death</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>negative regulation of control cell death</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Z disc</td>
</tr>
<tr>
<td>CA1</td>
<td><em>ATP2A1, ATP2A2, PLN</em></td>
<td>Biological Process</td>
<td>GO:0048878</td>
<td>chemical homeostasis</td>
</tr>
<tr>
<td></td>
<td><em>ATP2A1, PLN</em></td>
<td>Biological Process</td>
<td>GO:0006937</td>
<td>regulation of muscle contraction</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>regulation of heart contraction</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3.8

Associated diseases of genes with enriched GO terms.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Gene</th>
<th>Associated Disease</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA1</td>
<td>HSPB1</td>
<td>Axonal Charcot-Marie-Tooth disease type 2F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Distal hereditary motor neuronopathy type 2B</td>
</tr>
<tr>
<td>AA4</td>
<td>CRYAA</td>
<td>Multiple types of cataract 9</td>
</tr>
<tr>
<td></td>
<td>CRYAB</td>
<td>Multiple types of cataract 16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dilated cardiomyopathy-III</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Myofibrillar myopathy-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CRYAB-related fatal infantile hypertonic myofibrillar myopathy</td>
</tr>
<tr>
<td></td>
<td>CRYBB2</td>
<td>Multiple types of Cataract 3</td>
</tr>
<tr>
<td>CA1</td>
<td>ATP2A1</td>
<td>Brody myopathy</td>
</tr>
<tr>
<td></td>
<td>ATP2A2</td>
<td>Acrokeratosis verruciformis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Darier disease</td>
</tr>
<tr>
<td></td>
<td>PLN</td>
<td>Dilated cardiomyopathy-1P</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Familial hypertrophic cardiomyopathy-18</td>
</tr>
</tbody>
</table>

3.4.1 Duplication of HSPB1 and Health Disparities in African Americans

Gene HSPB1 is located in genomic duplication regions occurring more frequently in African Americans (Table 3.6), and is found in the cluster family of AA1, AA2, AA3, and AA4 (Table 3.5). For cluster AA1, only one GO molecular function term related to gene HSPB1 is significantly enriched (Cluster AA1 in Table 3.7). For cluster AA4, in addition to the same enriched GO molecular functions term, three more GO biological process terms and one GO cellular component term are found significantly enriched (Cluster AA4 in Table 3.7). In the genes with the enriched GO terms, four of them are known to be associated with diseases (Cluster AA1/AA4 in Table 3.8). Among these four genes, three of them are implicated in health disparities of African Americans.

Specifically, gene CRYAB is related to dilated cardiomyopathy and myofibrillar...
myopathy. African Americans were found at higher risk for idiopathic dilated cardiomyopathy compared with Caucasian, and this could not be explained by income, education, alcohol use, smoking, or history of some other diseases (Coughlin et al. 1993). Moreover, gene *CRYAA*, *CRYAB* and *CRYBB2* are all related to various types of cataract. It was reported that age-specific blindness prevalence was higher for African Americans compared with Caucasian, and cataract accounts for 36.8% of all blindness in African American, but for only 8.7% in Caucasian (Congdon et al. 2004).

We would like to emphasize that gene *HSPB1* is located in three CNVs that occur frequently in African Americans. Our results predict that *HSPB1* is a potential causal gene in these CNVs for health disparities. How could *HSPB1* duplication contribute to health disparity? Based on the direct interaction between *HSPB1* and *CRYAB* and the fact that both genes are expressed in Z-disc (Table 3.7), it is plausible that *HSPB1* may play an unknown role in cardiomyopathy. Alternatively, *HSPB1* might be involved in cataract, because *HSPB1*, *CRYAA* and *CRYAB* interact with each other and all can negatively regulate apoptotic process (Table 3.7). Studies suggested that lens epithelial cell apoptosis may be a common cellular basis for initiation of non-congenital cataract formation (Li et al. 1995), and inhibition of epithelial cell apoptosis may be one possible mechanism that inhibits cataract development (Nahomi et al. 2013). Our results here argue for further experimental studies to test the possible role of *HSPB1* CNVs in cardiomyopathy or cataract/blindness in African Americans.
3.4.2 Duplication of *ATP2A1* and Health Disparities in Caucasians

Gene *ATP2A1* in cluster CA1 is located in a genomic duplication region that occurs only in Caucasians (Table 3.6). We found that three genes in cluster CA1 are enriched with various GO biological process terms that involve *ATP2A1* (Cluster CA1 in Table 3.7). All of the three genes are related to diseases when they mutated (Cluster CA1 in Table 3.8). Our results here predict that *AP2A1* is a candidate causal gene for health disparity in this region.

How would *ATP2A1* influence health disparity? Among the diseases related to the pathogenic genes in cluster CA1, idiopathic dilated cardiomyopathy occurs less often in Caucasians than in African Americans (Coughlin et al. 1993). One possibility is that higher copies of *ATP2A1* may offer some benefits to Caucasians. Studies have shown that increased activity of sarco/endoplasmic reticulum Ca\(^{2+}\)-ATPase 1 (*SERCA1*), which is encoded by *ATP2A1*, can partially rescue the heart from •OH-induced injury (Hiranandani et al. 2006), and protect the heart from ischemia-reperfusion (I/R) injury (Talukder et al. 2007). Another possibility is that higher copies of *ATP2A1* only lead to moderate risk of cardiomyopathy in Caucasians, and this moderate effect is overshadowed by other genetics factors not covered by our CNV dataset.
In this study, we proposed a network clustering based approach to associate CNVs to health disparities in African and American. Gene clusters were inferred from two human gene/protein networks, HPRDNet and MultiNet, by MCL clustering algorithm with different parameters. Each cluster was ranked based on products of FDR values obtained from the right-tailed Fisher’s exact tests for enrichment of pathogenic genes or CNV-genes. Five clusters were consistently found to be ranked at first place and be enriched with both pathogenic genes and genes located in African-American or Caucasian CNVs. In cluster AA1, AA2, AA3 and AA4, gene \textit{HSPB1} is located in African-American-specific CNVs that are duplicated more frequently in African-Americans. In clusters CA1, gene \textit{ATP2A1} is located in a Caucasian-specific CNV that is duplicated only in Caucasians. All gene clusters are associated with certain diseases that occur more often in one population than in the other, which could be considered as results of the occurrence of corresponding CNVs. Although we only studied population-differential CNVs and did not consider the roles of other genetic factors, our computational studies have generated some interesting hypotheses for further experimental studies to understand health disparities in these diseases.
REFERENCES


Lee KW, Woon PS, Teo YY, and Sim K. 2012. Genome wide association studies (GWAS) and copy number variation (CNV) studies of the major psychoses: what have we learnt? *Neurosci Biobehav Rev* 36:556-571.


van Dongen S. 2000. Graph Clustering by Flow Simulation PhD. University of Utrecht.


APPENDIX A

CODES FOR GENE MAPPING OF SNPS AND CNV COORDINATES
// Setup connection to UCSC Genome Database
String username = "genome";
String password = "";
String url = "jdbc:mysql://genome-mysql.cse.ucsc.edu/hg19";
Class.forName("com.mysql.jdbc.Driver");
Connection con = DriverManager.getConnection(url, username, password);
Statement stmt = con.createStatement();
ResultSet rs = null;

// Search for gene names by SNP id
// Compose and submit SQL statements to UCSC Genome Database
rs = stmt.executeQuery("select distinct S.name, X.geneSymbol " +
"from snp138 as S, knownGene as G, kgXref as X " +
"where S.name = '" + "rs" + new_snp + "' AND X.kgId = G.name AND " +
"S.chrom = G.chrom AND " + "G.txStart <= S.chromStart AND " +
"G.txEnd >= S.chromEnd;";");

// extract results and write to output file
if (rs.next()){
    do {
        for (int i=1; i<3; i++) { output.print(rs.getString(i)+"\t"); }
        output.println();
    }while (rs.next());
} else { output.println("rs" + new_snp + "\t" + "gene_not_found"); }

// Search for gene names by CNV loci
// Compose and submit SQL statements to UCSC Genome Database
rs = stmt.executeQuery("select distinct X.geneSymbol, G.chrom, G.txStart, G.txEnd " +
"from knownGene as G, kgXref as X " +
"where ((G.txStart>" + begin + ") AND G.txEnd<" + end + ") or " +
"(G.txStart>" + begin + ") AND G.txStart<" + end + ") or " +
"(G.txEnd>" + begin + ") AND G.txEnd<" + end + ") or " +
"(G.txStart<" + begin + ") AND G.txEnd>" + end + ") AND " +
"G.kgId = G.name AND G.chrom = '" + chrom + ";";");

// extract results and write to output file
if (rs.next()) {
    do {
        for (int l=1; l<5; l++) { output.print(rs.getString(l)+"\t"); }
        output.println();
    }while (rs.next());
} else { output.println("not found"); }
APPENDIX B

CODES FOR RIGHT-TAILED FISHER’S EXACT TEST
//setup R engine
Rengine re = new Rengine (new String[] {}, false, null);
// Check if the session is working.
if (!re.waitForR()) { return; }

//Fisher's exact test for OMIM genes
for (int k=1; k<=nCluster; k++)
{
    if(AA_GeneClusters[k].get_q() != 0)
    {
        // obtain values and create the contingency table
        double cluster_q = AA_GeneClusters[k].get_q();
        double cluster_m = AA_GeneClusters[k].get_m();
        double cluster_nonOMIM = cluster_m - cluster_q;
        double other_OMIM = Q - cluster_q;
        double other_nonOMIM = N - Q - cluster_nonOMIM;
        re.eval("cluster = c(\"+cluster_q\",\"+cluster_nonOMIM\")");
        re.eval("other = c(\"+other_OMIM\",\"+other_nonOMIM\")");
        re.eval("tb = rbind(cluster, other)\");

        // perform the Fisher's exact test and obtain the p-value
        double p_OMIM = re.eval("fisher.test(tb,
                                alternative=\"greater\")\$p.value\").asDouble();
    }
}

//Fisher’s exact test for AA and CA genes
for (int k=1; k<=nCluster; k++)
{
    double cluster_AA_s = AA_GeneClusters[k].get_s();
    double cluster_CA_s = CA_GeneClusters[k].get_s();
    double cluster_m = AA_GeneClusters[k].get_m();
    double other_AA = S_AA - cluster_AA_s;
    double other_CA = S_CA - cluster_CA_s;

    // Fisher's exact test for AA only
    if(AA_GeneClusters[k].get_s() != 0)
    {
        // obtain values and create the contingency table
        double cluster_nonAA = cluster_m - cluster_AA_s;
        double other_nonAA = N-cluster_m-S_AA+cluster_AA_s;
        re.eval("cluster = c(\"+cluster_AA_s\",\"+cluster_nonAA\")");
        re.eval("other = c(\"+other_AA\",\"+other_nonAA\")");
        re.eval("tb = rbind(cluster, other)\");

        // perform the Fisher’s exact test and obtain the p-value
        double p_AA = re.eval("fisher.test(tb,
                                alternative=\"greater\")\$p.value\").asDouble();
    }

    // Fisher’s exact test for CA only
    if(CA_GeneClusters[k].get_s() != 0)
    {

}
// obtain values and create the contingency table
double cluster_nonCA = cluster_m - cluster_CA_s;
double other_nonCA = N-cluster_m-S_CA+cluster_CA_s;
re.eval("cluster = c("+cluster_CA_s","+cluster_nonCA")");
re.eval("other = c("+other_CA","+other_nonCA")");
re.eval("tb = rbind(cluster, other)";

// perform the Fisher’s exact test and obtain the p-value
double p_CA = re.eval("fisher.test(tb,
    alternative="greater")$p.value".asDouble();
APPENDIX C

CODES FOR FALSE DISCOVERY RATE CALCULATION
// Calculate FDR values
// fp is the File object of input file
Scanner pScan = new Scanner(fp);

// RstatementA contains a R statement to create a tuple of all p-values.
String RstatementA = "p=c("
while (pScan.hasNextLine())
{
   String line = pScan.nextLine();
   Scanner lineReader = new Scanner(line);
   lineReader.next();
   int tmp = (int) lineReader.nextDouble();
   if (tmp != 0)
   {
      lineReader.next();
      double p = lineReader.nextDouble();
      RstatementA = RstatementA + p + ", ";
      log.println("RstatementA"+RstatementA);
   }
}
RstatementA = RstatementA.substring(0, RstatementA.length()-2) + ");"

// create a tuple named "p"
re.eval(RstatementA);

// load robust-fdr routine
re.eval("source("D:/eclipse/workspace/test/robust-fdr.R")");

// RstatementD contains a R statement to run robust-fdr routine
String RstatementD = "robust.fdr(p, discrete=T, use8=F)$fdr";

// Obtain fdr values and save to an array
double[] fdr_disc = re.eval(RstatementD).asDoubleArray();
VITA

Yi Jiang was born in Suzhou, Jiangsu, China. He attended Nanjing University and obtained the Bachelors of Science degree in Applied Chemistry in May 2001. Yi completed the Master of Science degree in Pharmaceutical Sciences at University of Florida before he entered the Computer Sciences Program at University of Tennessee at Chattanooga. Yi worked as teaching and research assistants in Department of Computer Science, and graduated with a Master of Science degree with thesis option in Computer Science in December 2014. Yi’s research interests include data analysis, database management and computer programming.