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Assessing Risk Factors Pre-Disposing Individuals to Noise Induced Hearing Loss

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This is to certify that the doctoral dissertation by

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Abstract

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Martin D. Slade

MPH, Yale University, 2001

BS, Syracuse University, 1980

Dissertation Submitted in Partial Fulfillment

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Abstract

Noise induced hearing loss (NIHL) has the highest prevalence of all occupational diseases in the manufacturing sector accounting for one out of every nine recordable illnesses. Currently, after accounting for known risk factors, a large amount of unexplained variance remains in statistical models of NIHL. The purpose of this study was to determine the underlying factors pre-disposing people to NIHL as well as the association between early and future occupational hearing loss. The ecological model of health behavior provided the theoretical framework for this study. The key research questions were: which demographic factors (age, gender, and race) are associated with accelerated occupational NIHL; is there an association between hearing loss early in an individual's work history and accelerated occupational NIHL later in their career; and in a multivariate adjusted model, which demographic, lifestyle, and occupational factors are associated with NIHL and are there significant interactions between the factors. A total of 4,894 subjects were followed for up to 13 years with 708 (14.5%) of them developing hearing impairment. Increasing age and being of White race were associated with an increased risk of developing hearing impairment. The sex of the worker and the annualized change in noise notch over the worker's first five years were found to interact with regard to the risk of developing hearing impairment. The observed relationship between early occupational hearing loss and risk of hearing impairment will allow companies to incorporate criteria that trigger additional education and, possibly, re-assignment of at-risk employees to jobs within their company with lower noise exposure. Through this type of policy, the societal burden of hearing loss can be reduced.

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Dedication

This dissertation is dedicated to my wife, Maria.

Acknowledgement

I would like to acknowledge all who played a role in my academic accomplishment. First and foremost is my wife whose encouragement allowed me to keep going throughout the tough times. My committee members gave incredibly helpful feedback throughout the process. Many thanks to Dr. Robert Marino and Dr. Gudeta Fufaa for their guidance and effort.

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Chapter 1: Introduction

The field of occupational medicine focuses on prevention of disease and promotion of wellness among workers (Roberts, 1978). It can be considered a subspecialty of preventive medicine (Howe, 1975). In addition to clinical skills, practitioners of occupational medicine are trained to have the necessary tools to uncover work related diseases (Gochfeld, 2005). Therefore, an important component of occupational medicine is epidemiology as it is a field concerned with population health: in this case, worker health. This enables the field to recommend changes in the working environment, incorporate surveillance programs, and be part of research studies focused on reducing occupational disease and injury.

Noise induced hearing loss (NIHL) has the highest prevalence of all occupational diseases in the manufacturing sector, accounting for one out of every nine recordable illnesses (Hammill, 2017; NIOSH, 2014). Among Americans, approximately 30 million are exposed to noise levels that are considered hazardous, and 10 million suffer from permanent NIHL (Doosti et al., 2014; Rabinowitz, 2000). The resultant disability associated with noise exposure permeates the entire spectrum of occupations from agriculture workers, to factory workers, to those serving in the United States military. Within the United States military, a substantial number of service members sustain such significant hearing loss by mid-career that they are either forced to change their military specialty or involuntarily leave the service (Wells et al., 2015). In fact, it has been noted that even with the use of traditional hearing protection devices, military personnel continue to have high prevalence of NIHL (Kopke et al., 2015). It has been reported that 46% of enlisted sailors have compensable hearing loss at the end of their career (Trost &

Shaw, 2007). Hearing loss and the associated complaint of tinnitus are the top two disorders observed at the Veterans Administration with a resultant cost of over $1.2 billion in 2009 alone (Saunders & Griest, 2009).

Previous studies have shown NIHL to be a result of physical or mechanical mechanisms (Nakagawa et al., 1997; Rabinowitz, 2000). More recent studies have noted that there is a metabolic component to NIHL such that oxidative stress is increased in noise (Daiber et al., 2019; Fetoni et al., 2019; Le, Straatman, Lea, & Westerberg, 2017). High levels of noise exposure results in structural changes in the hair cell membrane resulting in the production of reactive oxygen species (ROS). The body is unable to fully neutralize these free radicals and, as a result, the inner and outer hair cells die through the process of apoptosis or necrosis (Kopke et al., 2015). The resultant hearing loss is believed to be irreversible (Śliwińska-Kowalska & Zaborowski, 2017).

Background

Hearing loss is extremely prevalent in today's world. It has been estimated by the World Health Organization (WHO) that hearing loss affects between 700 million and 1 billion people worldwide and that 36 to 51% of these people have severe or disabling hearing loss (WHO, 2015). There are several known factors associated with hearing loss including age (Lin, Thorpe, Gordon-Salant, & Ferrucci, 2011), gender, race, and genetic expressions (Curhan & Curhan, 2016; Daniel, 2007). But the largest factor contributing to hearing loss over time is cumulative exposure to noise (Lin et al., 2011; Mills, 1973; NIH, 2015; Tak, Davis, & Calvert, 2009). The period in history where the detrimental effect of noise on hearing acuity was first uncovered is unknown, but certainly by the

20th century, metal workers involved in the forging process had established occupational noise to be associated with hearing loss (Thurston, 2013).

NIHL is the result of hair cells (cilia) being destroyed in the organ of Corti, which resides within the cochlear portion of the inner ear. The typical person begins life with roughly 16,000 cilia (Bokolia & Mishra, 2015). Once destroyed, these hair cells do not regenerate (Revuelta et al., 2017), thus their damage is irreversible. On top of this, prior to hearing loss becoming detectable, between one-third and one-half of these hair cells will already have been damaged or destroyed (Daniel, 2007). It is, therefore, especially critical to be able to detect the onset of measurable hearing loss as quickly as possible.

From an evolutionary perspective, the ability to hear was critical for awareness of potential sources of danger (Basner et al., 2014; Hughes & Jones, 2003). But even today, hearing loss can have profound effects upon a person’s life. Loss of hearing diminishes one’s ability to listen to enjoyable sounds including music and the sounds of nature. Another issue associated with having prevalent hearing loss is increased difficulty in communication, which can result in social isolation (Danielsson, Pichora-Fuller, Dupuis, & Rönnberg, 2015). These issues may lead to mental health problems, including anxiety and depression, as well as reductions in quality of life and well-being (Chia et al., 2007; Dalton et al., 2003; Jayakody et al., 2018; Tambs, 2004). Decreased cognitive function as well as lowered attention to tasks have also been associated with hearing loss. These may be related to the increased risk of accidents and falls among those with hearing loss (Jiam, Li, & Agrawal, 2016). Importantly, hearing loss has also been associated with higher mortality (Basner et al., 2014).

In 1983, the Occupational Safety and Health Administration (OSHA) mandated workplace hearing conservation programs with the goal of reducing occupational hearing loss (OSHA, 1983). The regulation stated that a hearing conservation program be provided for all workers with daily noise exposures greater than 85 dBA time weighted average. It also defined the permissible exposure level at 90 dBA, a level above which the use of hearing protection devices is mandatory (Dobie, 1985). There are five basic program elements to the resultant occupational hearing conservation programs instituted by industry. These program elements are: (1) noise surveys, (2) education, (3) noise control, (4) hearing protection devices, and (4) audiometric monitoring (Royster, Royster, Driscoll, & Layne, 2003).

Noise Surveys

In order to understand which employees need to be enrolled in the hearing conservation program, it is imperative that the noise levels associated with the different jobs within the organization be measured and recorded. These noise dosimetry measurements must be repeated whenever there is a substantial change to a job such that the noise exposure levels may change. The results of these surveys enable the employer to determine which employees are subjected to a time weighted average of at least 85 dBA, and which of those employees are subjected to a time weighted average of at least 90 dBA, as these are thresholds within the OSHA standard.

Education

Each employee in the hearing conservation program must receive education regarding the deleterious effects of noise. The education must also explain how hearing protective devices can help prevent NIHL. Importantly, education session(s) can help to motivate employees to follow the rules of the hearing conservation program, as engaged employees are more likely to fully participate.

Noise Control

Primary prevention would eliminate the hazard in the workplace. Thus, engineering could be used to reduce the noise that employees are subjected to. Although the best approach, this is not always feasible due to process or cost issues. For those workers where hazardous noise levels cannot be sufficiently reduced through engineering, administrative noise controls can be put into place. A typical administrative noise control would mandate that a worker can only be exposed to the noise hazard in this job for a portion of their job shift. For example, a worker may only be able to perform a particular job for 4 hours a day due to the noise exposure level associated with that job. The rest of the worker's shift would be in an area with lower noise exposure.

Hearing Protection Devices

According to the 1983 OSHA regulation, hearing protection devices must be made available to workers in a hearing conservation program free of charge. Additionally, as there are many different types of hearing protection devices and individual workers have different preferences, the employer is required to provide a choice of devices to the worker. The employer needs to educate workers in the proper use of these devices to ensure the greatest efficacy of the device. Lastly, management needs to enforce the use of these hearing protection devices in areas of hazardous noise.

Audiometric Monitoring

According to the 1983 OSHA regulation, each worker enrolled in the hearing conservation program should receive a baseline audiogram when they enter the program and then yearly audiograms thereafter. These audiograms must test the worker's threshold hearing level separately for each ear at the following frequencies: 500 Hz, 1k Hz, 2k Hz, 3k Hz, 4k Hz, and 6k Hz. The technician that performs the audiometric tests needs to have an audiologist, otolaryngologist, or physician oversee them. The audiograms must be reviewed in order to determine if the worker has had a significant threshold shift, that is, a significant loss of hearing (Mirza & Kirchner, 2018; Suter, 2002). Unless explainable for some other reason, these significant threshold shifts are attributable to occupational noise and must be reported to the governing agency.

Although hearing conservation programs have been in place for over 30 years, NIHL remains a significant public health problem. There is building evidence of a genetic influence on susceptibility to NIHL. According to the American National Standard Institute, the variability (defined as the range between the 10th and 90th percentiles) in hearing loss at 4 kHz among male workers exposed to 100 dBA noise for 30 years is 60 dB (ANSI, 2006). Although some of this variability may be due to misclassification of noise exposure or errors in the measurement of hearing threshold, genetic variation likely plays a significant role. In fact, it has been suggested that up to 60% of NIHL cases may be the result of genetic factors (Bovo, Ciorba, & Martini, 2007). A cross-sectional retrospective study of 2,407 noise exposed workers in a Sao Paulo, Brazil metal working company found a phenotype, fair iris color, defined as green, blue, hazel or grey eye color, to be associated with propensity for NIHL (Da Costa, Castro, & Macedo, 2008). Another study of 343 Brazilians noted that an interleukin-6 polymorphism was associated with greater likelihood of NIHL (Braga, Maciel, Marchiori, & Poli-Frederico, 2014). The idea that an individual's genetic makeup can affect their response to noise exposure means that there will be a subset of people with a greater propensity for NIHL.

Even considering all the research conducted to date, the current ability to predict those people with an increased propensity for NIHL is quite limited (Bovo et al., 2007; Themann et al., 2015). This results in at least two issues. The regulations in place to protect workers from NIHL are based upon normal worker populations and therefore may not be adequate to protect workers predisposed to NIHL. Additionally, clinical trials to evaluate potential interventions, including pharmaceutical agents to prevent NIHL, require extremely large numbers of subjects as the majority of control subjects may not experience measurable hearing loss (Kopke et al., 2015). Realizing that the use of genetic information may not help these issues, at least in the short term, an alternative approach would be useful. The ability to use an individual's early work experience audiometric test data to predict future propensity for NIHL would be an important tool.

Problem Statement

At the latter part of the 20th century,

NIHL affected over 10 million people within the United States, second only to aging as the greatest cause of hearing loss (Alberti, 1998; Lang, 1994). In 2012, the number of people aged 20 to 69 years in the United Sates with an audiometric notch (an indication of NIHL) was estimated to be 39.4 million (Carroll et al., 2017). Noise induced occupational hearing loss results in huge costs, not only due to the financial burden associated with workers compensation claims but also in terms of the quality of the employee's life. In 1983, workplace hearing conservation programs were mandated by OSHA with the purpose of substantially reducing occupational hearing loss (OSHA, 1983). This standard has been in place for over 30 years during which various approaches have been undertaken to remedy the NIHL problem. These approaches have included the incorporation of engineering controls to reduce the ambient noise level, the use of various types of hearing protection devices, administrative controls that reduce the time employees spend in high noise areas, and educational programs for employees regarding noise and hearing. Nonetheless, NIHL remains a significant problem. Additionally, some occupations, including the U.S. military, continue to create even louder work environments as, for instance, the increased power required for ever greater maneuverability and efficiency of aircraft requires a commensurate increase in noise (Aubert & McKinley, 2011). Relatively recently, research into pharmaceutical interventions to reduce NIHL have started to be pursued as the effectiveness of mechanical hearing protection devices seem insufficient to address the problem. The development of a safe and effective pharmaceutical prophylactic for NIHL coupled with the ability to identify those individuals at increased risk for NIHL would allow for targeted intervention. Such a targeted intervention would minimize the number of people exposed to the intervention, thereby minimizing both the economic cost of the intervention and the number of individuals put at risk for any sort of adverse effect from the intervention.

Research regarding pharmaceutical interventions to prevent NIHL have shown much success in animal studies (Kopke et al., 2004; Kopke et al., 2000). Translational medicine, taking the animal success to humans, however, has had less success. To my knowledge, there have only been three large randomized, placebo-controlled, double-blind clinical trials to ascertain the safety and efficacy of pharmaceutical interventions on noise inducing hearing loss, and only one of these has been published (Kopke et al., 2015). Each of these three studies suffered from one significant issue, namely, that among the placebo group, the majority of subjects do not experience significant hearing loss during the relatively limited time duration trial. In each study, however, there are a relatively small percentage of individuals, approximately 20%, that do demonstrate significant hearing loss. Due to the underlying nature of statistics, when performing statistical analyses to determine the effectiveness of an intervention, when the rest of the placebo population is included, it becomes extremely difficult to show a statistically significant effect.

There is a gap in the literature with regard to the underlying factors that predispose certain individuals to NIHL. The ability to predict the risk, or propensity, of a person to experience NIHL would reduce the number of workers experiencing NIHL. From an NIHL research point of view, this predictive ability would allow for inclusion criterion that limits the study population to those with an increased risk of accelerated hearing loss. This would allow trials to be conducted with a reasonable number of subjects (on the order of many hundreds as opposed to many thousands). Currently, even after accounting for known risk factors such as noise, age, race, gender, smoking, diabetes, and solvent exposure (Agrawal, Platz, & Niparko, 2009; Daniel, 2007; Johnson et al., 2017; Kurmis & Apps, 2007), there remains a large amount of unexplained variance in statistical models of NIHL. A better predictive model of NIHL would be extremely useful to researchers and society in general. It is possible that the observed change in hearing early in an individual's occupational career may serve as an independent predictor for the rate of hearing loss that the individual will experience in the future. A literature review has not revealed any published papers attempting to determine the risk of future occupational hearing loss as a function of early career hearing loss.

Purpose of the Study

The purpose of this study is to determine the underlying factors predisposing people to NIHL as well as the association between early occupational hearing loss and future occupational hearing loss. In order to address this gap in knowledge, a working definition of NIHL will be defined using a noise notch criterion as NIHL is characterized by a loss of hearing in the mid-frequencies with lesser loss at the extremes of the measured audiometric test frequencies. A quantitative research approach will be used to determine the demographic, occupational (including early career hearing loss), and lifestyle factors that are associated with NIHL along with their effect sizes.

Research Questions and Hypotheses

After a review of the current NIHL literature, the following research questions, as well as hypotheses, have been developed. Chapter 3 will include a more detailed discussion regarding the overall nature of the study.

RQ1: Which demographic factors (age, gender, and race) are associated with increased probability of accelerated occupational NIHL given similar noise exposure?

H_01_1: There is no association between age and accelerated occupational NIHL later in an individual's career.

H_11_1: There is an association between age and accelerated occupational NIHL later in an individual's career.

H_01_2: There is no association between gender and accelerated occupational NIHL later in an individual's career.

H_11_2: There is an association between gender and accelerated occupational NIHL later in an individual's career.

H_01_3: There is no association between race and accelerated occupational NIHL later in an individual's career.

H_11_3: There is an association between race and accelerated occupational NIHL later in an individual's career.

RQ2: Is tobacco use associated with NIHL given similar noise exposure?

H_02: There is no association between smoking status and accelerated occupational NIHL later in an individual's career.

H_12: There is an association between smoking status and accelerated occupational NIHL later in an individual's career.

RQ3: Which health conditions (BMI and diabetes) are associated with NIHL given similar noise exposure?

H_03_1: There is no association between BMI and accelerated occupational NIHL later in an individual's career.

H_13_1: There is an association between BMI and accelerated occupational NIHL later in an individual's career.

H_03_2: There is no association between diabetes and accelerated occupational NIHL later in an individual's career.

H_13_2: There is an association between diabetes and accelerated occupational NIHL later in an individual's career.

RQ4: Is there an association between hearing loss early in an individual's work history and accelerated occupational NIHL later in their career?

$H_0$4: There is no association between hearing loss early in an individual's work history and accelerated occupational NIHL later in their career.

$H_1$4: There is an association between hearing loss early in an individual's work history and accelerated occupational NIHL later in their career.

RQ5: In a multivariate adjusted model, which demographic, lifestyle, and occupational (including early career hearing loss) factors are associated with NIHL given similar noise exposure and are there significant interactions between the factors?

Theoretical and Conceptual Frameworks

Occupational NIHL is the result of health behaviors. Any person's health behaviors are the result of various influences, each from a different source. The ecological model of health behaviors developed by McLeroy and others suggests that there are five sources of influence on health behaviors (McLeroy, Bibeau, Steckler, & Glanz, 1988). These five sources are: (1) intrapersonal factors; (2) interpersonal processes and primary groups; (3) institutional factors; (4) community factors; and (5) public policy (Sallis et al., 2015).

As with other ecological models of health behavior, social and psychological influences are incorporated into the model while environmental and policy aspects of behavior are emphasized (Sallis et al., 2015). By their very nature, ecological models ensure the consideration of different levels of influence, both individually and interactively. Thus, they allow for comprehensive interventions to be developed and implemented. Ecological models conclude that it takes both individual-level and policy/environmental-level interactions to obtain significant change in behavior. As occupational NIHL can be thought of as the result of individual behavior and company/government policies, the ecological model of health behavior was used as the theoretical framework for this dissertation.

In addition to the theoretical framework, there is also a conceptual framework underpinning this research topic, namely, the theory that NIHL is the result of chronic exposure to loud noise defined as a sound level above 85 dBA. This type of noise exposure initially results in damage to the hair cells in the cochlea, a part of the organ of Corti. As these hair cells are vibrated by acoustic waves that reach this portion of the ear and, in turn, transform the mechanical energy into electrical signals through the eighth cranial nerve fibers. Initially, it is the outer hair cells within the cochlea, those that are responsible for high-frequency auditory stimuli, that are damaged. For these purposes, higher frequencies are in the 3 to 6 kHz range and are above the primary speech frequencies of 0.5 to 2 kHz. Over time, with continued noise exposure, the inner hair cells are also damaged, resulting in low-frequency (primary speech frequencies) hearing loss. With increased intensity and length of exposure, damage to the cochlea hair cells becomes irreversible. As the blood flow to the cochlea decreases, the hair cells either disappear or become fused into large cilia, supporting structures disintegrate, and finally the nerve fibers degenerate (Hong, Kerr, Poling, & Dhar, 2013).

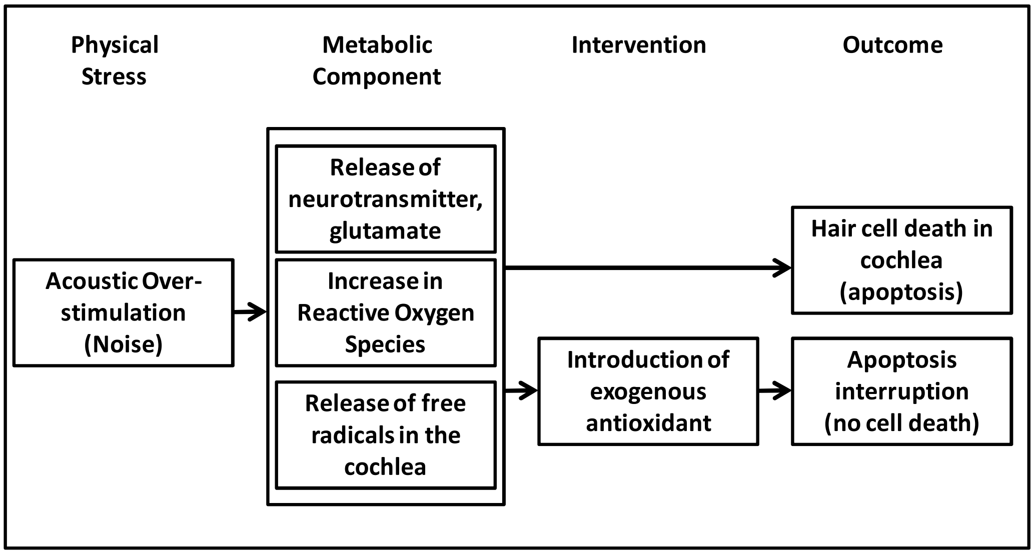
The pathophysiology underlying NIHL are believed to be two-fold. The first is a mechanical damage model whereby a pressure wave enters the ear resulting in vibratory action of the cochlear cilia. Given sufficient energy, this physical trauma leads to structural damage of the hair cells. The second is a metabolic model, as NIHL has been found to have a metabolic component (Yamane et al., 1995). It is hypothesized that acoustic over-stimulation can result in a large release of glutamate, a neurotransmitter, at the synapse of the ear's inner hair cell, causing a quick increase in ROS and a release of free radicals in the cochlea. This process results in neuronal or hair cell death through the process of apoptosis (Kopke et al., 2015).

Glutathione, or GSH, is an antioxidant that acts within the ear's cochlea. It has been suggested that GSH may prevent damage to the ear's hair cells by preventing the damage caused by free radicals (Ohinata, Yamasoba, Schacht, & Miller, 2000). Exposure to loud noise can cause a depletion of GSH, thereby allowing the hair cells to become damaged. In the event of acoustic insult, the introduction of exogenous antioxidants may overcome the depletion of GSH, thereby preventing apoptosis of the cochlear hair cells and, therefore, reducing or preventing NIHL. This process could be enhanced if the antioxidant that is introduced also stimulates the endogenous antioxidants.

One antioxidant that has been extensively tested in the lab has been N-acetylcysteine (NAC). In a small human trial consisting of 53 subjects, NAC, taken orally, has been shown to be associated with reduced temporary threshold shifts (hearing loss) among subjects exposed to moderate levels of noise (Lin et al., 2010). This effect was most notable among subjects with GSTM1-null and GSTT1-null genotypes, which suggests a genetic component to the effectiveness of NAC on the prevention of NIHL. Therefore, the genetic makeup of individuals will be associated with the propensity to experience NIHL. The metabolic theory for NIHL is depicted in Figure 1.

Figure 1

Metabolic Theory for Noise Induced Hearing Loss



Any behavioral, demographic, or occupational factors that are associated with propensity for NIHL may function through their effect on the previously described metabolic process. These predisposing factors will affect the observed relationship between noise exposure (level and duration) and rate of hearing loss.

Definition of Terms

Hearing threshold level is the level of sound, in dB, that can be heard during audiometric testing in a quiet setting. During the typical audiometric test in this corporation, seven frequencies (500 Hz, 1k Hz, 2k Hz, 3k Hz, 4k Hz, 6k Hz, and 8k Hz) are tested separately in each ear. Sound amplitude is varied in 5 dB increments.

HyGenius is proprietary software owned by the corporation. It is used to store, analyze, and report industrial hygiene data. Included within its database is information from all noise exposure measurements taken by the corporation.

Medical Claims Data refers to the database that includes medical claim data, including pharmacy claims, for employees of the corporation as the corporation is a self-insured entity. The data does not include medical chart information (e.g., blood pressure measurements) but only houses insurance claim information including diagnosis (ICD-9) codes and procedure (CPT) codes.

Occupational Health Manager (OHM) is a commercially available multi-module software system used by the corporation to collect, store, analyze, and report data from their hearing conservation program. OHM includes all of the corporation's audiometric testing data.

PeopleSoft is a commercial human resource software system that stores employee data including demographics, employee status, workplace location, department and job assignment, and scheduled work hours.

*Standardized job*s are the result of a standardization process conducted in 2000 by the corporation's senior industrial hygiene manager. Due to the sheer volume of different job titles within the corporation, jobs were aggregated and standardized such that each standardized job consisted of jobs that had similar exposures. This standardization also allows for linkages between PeopleSoft and HyGenius databases.

Time-weighted Average (TWA) is the average sound level normalized to 8 hours (a typical worker shift length). It is calculated as:

$$TWA = 16.61\, log\left(\frac{D}{100}\right) + 90\; dBA$$

where D is the dose and log designates log base 10.

Significance

This research will fill a gap in knowledge by focusing not only on the demographic, occupational, and lifestyle factors associated with NIHL among a cohort of individuals with occupational noise exposure, but also by accessing the likelihood of future NIHL based upon an individual's early career audiometric test data. This project is unique as it addresses both a working definition of NIHL and evaluates the association of the main effects of the explored factors on noise induced hearing loss. The knowledge of the factors associated with a greater propensity for NIHL, notably an individual's early hearing loss, will allow for targeted interventions in the workplace to reduce noise-induced hearing loss among workers. The resultant knowledge will also enable greater efficiency in future NIHL research trials as inclusion criteria could be specified so that only those subjects with a propensity for accelerated hearing loss would be eligible for the trial.

Overall, this study's findings may result in positive social change, as the ability to predict those individuals with greater propensity for NIHL may allow for policy changes that ultimate will reduce the rates of significant hearing loss. This, in turn, will increase the quality of life for those people who otherwise would have had substantially greater hearing loss. It should also decrease the overall financial cost of hearing loss to society through prevention.

Assumptions

Various assumptions are made with regard to this study. They are delineated below:

1. It is assumed that the standardization of jobs was accurate insofar as noise exposure was similar across the various jobs combined into a standardized job.
2. It is assumed that all workers in a given standardized job have identical noise exposure.
3. It is assumed that the random industrial hygiene measurements of noise accurately captured the average noise exposure for that job.
4. It is assumed that audiometric measurements were accurate measures of the individual's hearing threshold levels on the day that they were taken.
5. It is assumed that the medical claims data capture all covered encounters. It is also assumed that the medical records are accurate insofar as coding of diagnoses and procedures.

Limitations

The study population is made up of United States aluminum manufacturing workers. Although the physiology of hearing and the pathology of hearing loss should be similar among people working in other sectors, it is possible that there are unmeasured differences that make generalizability limited to the United States manufacturing workforce. Additionally, the frequency spectrum of noise was not measured and, therefore, it is possible that similar noise exposure levels consisting of different frequencies than those of this study may yield different results. Lastly, the equal energy assumption underlying the concept of a TWA may have some limitations.

Summary

NIHL has been, and remains, an important public health concern. Previous research has determined factors associated with NIHL including noise, age, race, gender, smoking, diabetes, and solvent exposure. However, there is still much individual variation after adjusting for known risk factors. Noise exposure regulations that have been put in place to protect workers from NIHL are based upon normal worker populations and, therefore, may not be adequate to protect workers predisposed to NIHL. Due to the large unexplained individual variation in hearing loss, clinical trials to evaluate potential interventions require extremely large numbers of subjects as the majority of control subjects may not experience measurable hearing loss. It is hoped that the results from this study will enhance the state of knowledge regarding NIHL. In particular, it is hoped that an early evaluation methodology will allow for determination of those individuals with a higher propensity for NIHL as this would let policies to be put in place to further protect workers, ultimately reducing the prevalence of NIHL across the population.

In the next section, Chapter 2, the current literature regarding NIHL is reviewed. The knowledge gaps regarding predictors of NIHL are noted. Chapter 3 discusses the specific research questions as well as the methodology used in the study to answer those questions. Chapter 4 describes the study population as well as the results of the statistical analyses. Lastly, Chapter 5 discusses the conclusions derived from the study including their impact on population health.

Chapter 2: Literature Review

This chapter describes the literature of NIHL among working populations. Specifically, the epidemiological evidence associated with the burden of occupational noise-induced hearing loss are examined. The chapter frames the need for further study of occupational NIHL from a longitudinal perspective in order to determine early work life predictors of accelerated hearing loss. NIHL has been identified as the most common occupational injury in the United States workforce. A substantial literature exists regarding occupational NIHL. This literature will be reviewed in the current chapter.

Studies have described the epidemiology of NIHL in occupational settings. Although the numerous published studies have described prevalence of occupational NIHL, evaluated the methodologies utilized in evaluation hearing and hearing loss, and ascertained that people vary with regard to their propensity for hearing loss, the studies have not been able to identify populations of people with a high likelihood of accelerated hearing loss prior to it occurring. This chapter will describe the state of knowledge regarding available research related to occupational NIHL and demonstrate the gap in this knowledge that needs to be completed in order to be able to identify individuals at risk of accelerated NIHL in the occupational setting.

Literature Search and Methods

I conducted a comprehensive search of published literature. PubMed, Medline, and Google Scholar search engines were utilized to conduct the literature search for peer-reviewed literature. Additionally, the OSHA and the National Institute for Occupational Safety (NIOSH) websites were viewed to determine the regulations and guidelines regarding noise-induced hearing loss that each agency has put into place to protect United States workers. Table 1 lists the criteria utilized for the literature review.

Table 1

Search Words Utilized for Literature Review

Search Words	PubMed	Scopus	Google Scholar
Occupational noise induced hearing loss	3,537	3,848	16,500
Occupational NIHL	3,481	505	4,150
NIHL	7,949	996	2,970
Noise induced hearing loss	8,265	9,059	17,200
Susceptibility NIHL	395	139	935
Susceptibility noise induced hearing loss	404	449	17,300
Occupational noise sensorineural hearing loss	3,319	261	3,230
Longitudinal noise induced hearing loss	111	124	14,400
Longitudinal NIHL	106	20	517

Initially, the titles and abstracts were reviewed to ascertain whether a published document should be read in its entirety or discarded because it was not relevant to the study question. These documents were comprised of peer-reviewed journal articles, textbooks, and official government publications. Of those documents that were read in their entirety, a total of 114 resources, listed in Appendix A, were ultimately found to have relevance to the study. Additionally, if one of these 114 resources referenced a document that was both relevant and not previously considered, then it was included in this dissertation and included in the References section.

Theoretical Framework

The theoretical framework for this dissertation is founded upon the idea that multiple influences acting in concert result in disease and injury. For this dissertation, the injury of interest is occupational NIHL, a result of health behaviors. According to the ecological model of health behaviors (McLeroy et al., 1988), health behaviors are influenced by five separate sources: (1) intrapersonal factors; (2) interpersonal processes and primary groups; (3) institutional factors; (4) community factors; and (5) public policy (Sallis et al., 2015). The ecological model of health behaviors provides a framework to bring together behavioral, social, policy, and, importantly, biological aspects of the human experience into an epidemiological study. The model suggests that the interaction between these various influences should be considered when developing a public health intervention (Ehrman, Gordon, Visich, & Keteyian, 2009; Thurston, 2013).

As with other ecological models of health behavior, social and psychological influences are incorporated into the model while environmental and policy aspects of behavior are emphasized (Sallis et al., 2015). By their very nature, ecological models ensure the consideration of different levels of influence, both individually and interactively. Thus, they allow for comprehensive interventions to be developed and implemented. Ecological models conclude that it takes both individual-level and policy/environmental-level interactions to obtain significant change in behavior. As occupational NIHL can be thought of as the result of individual behavior and company/government policies, the ecological model of health behavior was used as the theoretical framework for this dissertation.

In addition to the theoretical framework, there is also a conceptual framework underpinning this research topic, namely, the theory that NIHL is the result of chronic exposure to loud noise defined as a sound level above 85 dBA. This type of noise exposure initially results in damage to the hair cells in the cochlea, a part of the organ of Corti. These hair cells are vibrated by acoustic waves that reach this portion of the ear and, in turn, transform the mechanical energy into electrical signals through the eighth cranial nerve fibers. Initially, it is the outer hair cells within the cochlea, those that are responsible for high-frequency auditory stimuli, that are damaged. For these purposes, higher frequencies are in the 3 to 6 kHz range and are above the primary speech frequencies of 0.5 to 2 kHz (Baken & Orlikoff, 2000). Over time, with continued noise exposure, the inner hair cells are also damaged, resulting in low-frequency (primary speech frequencies) hearing loss. With increased intensity and length of exposure, damage to the cochlea hair cells becomes irreversible. As the blood flow to the cochlea decreases, the hair cells either disappear or become fused into large cilia, supporting structures disintegrate, and finally the nerve fibers degenerate (Hong et al., 2013).

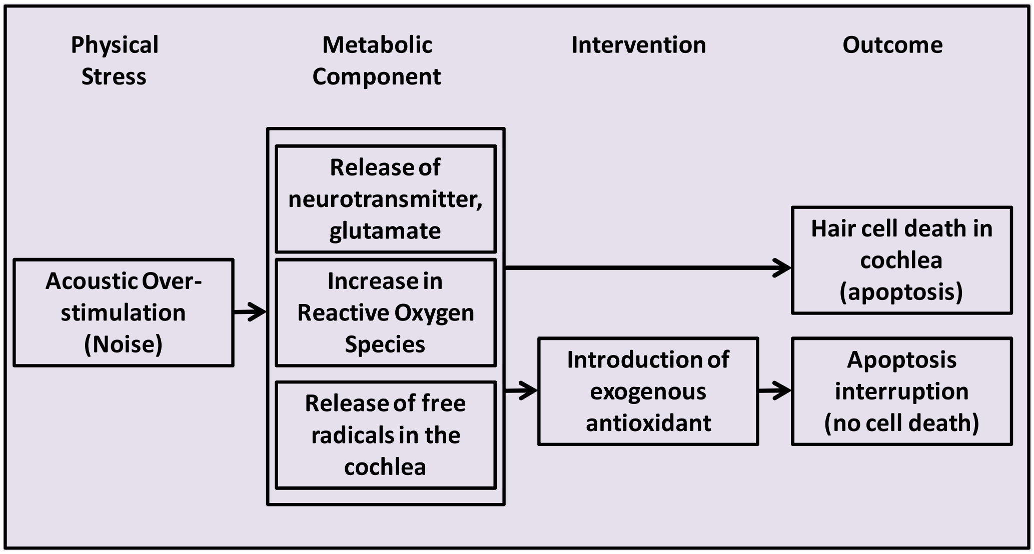
The pathophysiology underlying noise induced hearing loss are believed to be two-fold. The first is a mechanical damage model whereby a pressure wave enters the ear, resulting in vibratory action of the cochlear cilia. Given sufficient energy, this physical trauma leads to structural damage of the hair cells. The second is a metabolic model, as NIHL has been found to have a metabolic component (Yamane et al., 1995). It is hypothesized that acoustic over-stimulation can result in a large release of glutamate, a neurotransmitter, at the synapse of the ear's inner hair cell, causing a quick increase in ROS and a release of free radicals in the cochlea. This process results in neuronal or hair cell death through the process of apoptosis (Kopke et al., 2015).

GSH is an antioxidant that acts within the ear's cochlea. It has been suggested that GSH may prevent damage to the ear's hair cells by preventing the damage caused by free radicals (Ohinata et al., 2000). Exposure to loud noise can cause a depletion of GSH, thereby allowing the hair cells to become damaged. In the event of acoustic insult, the introduction of exogenous antioxidants may overcome the depletion of GSH, thereby preventing apoptosis of the cochlear hair cells and, therefore, reducing or preventing noise induced hearing loss. This process could be enhanced if the antioxidant that is introduced also stimulates the endogenous antioxidants.

One antioxidant that has been extensively tested in the lab has been N-acetylcysteine (NAC). In a small human trial consisting of 53 subjects, NAC, taken orally, has been shown to be associated with reduced temporary threshold shifts (hearing loss) among subjects exposed to moderate levels of noise (Lin et al., 2010). This effect was most notable among subjects with GSTM1-null and GSTT1-null genotypes, which suggests a genetic component to the effectiveness of NAC on the prevention of NIHL. Therefore, the genetic makeup of individuals will be associated with the propensity to experience noise induced hearing loss. The metabolic theory for noise induced hearing loss is depicted in Figure 2.

Figure 2

Metabolic Theory for Noise Induced Hearing Loss



Any behavioral, demographic, or occupational factors that are associated with propensity for NIHL may function through their effect on the previously described metabolic process. These predisposing factors will affect the observed relationship between noise exposure (level and duration) and rate of hearing loss.

Noise

Prior to discussing NIHL, in is important to understand the concept of noise as it relates to this subject. Noise is technically a subset of sound; it is unwanted sound (Foreman, 1990). Thus, in many ways, noise is a subjective term. Sound, however, is objective. Sound emanates from a source, travels through a medium, and reaches a receiver. For the purposes of this thesis, the medium through which the sound energy travels is air and the receiver is the human ear. The source of sound is a vibrating object which sends out pressure waves through the air. These oscillating (sinusoidal) fluctuations in ambient air pressure stimulate the ear's receptors, which respond by generating neural impulses that the brain receives and perceives as sound. As the pressure variation is sinusoidal, it has associated with it a frequency and an amplitude. The frequency is the number of cycles per second, also known as Hertz (Hz). The change in the magnitude of the sound pressure waves is the amplitude and is measured in decibels (dB; Foreman, 1990). Explicitly, the loudness of sound is measured in decibels, which is the logarithmic ratio of a sound pressure to a reference sound pressure as described by:

$$L_p = 20 \log_{10} (p/p_0),$$

where:

L_p = Sound pressure level, dB

p = Root mean square sound pressure

p_0 = Reference sound pressure (typically, 20μPa)

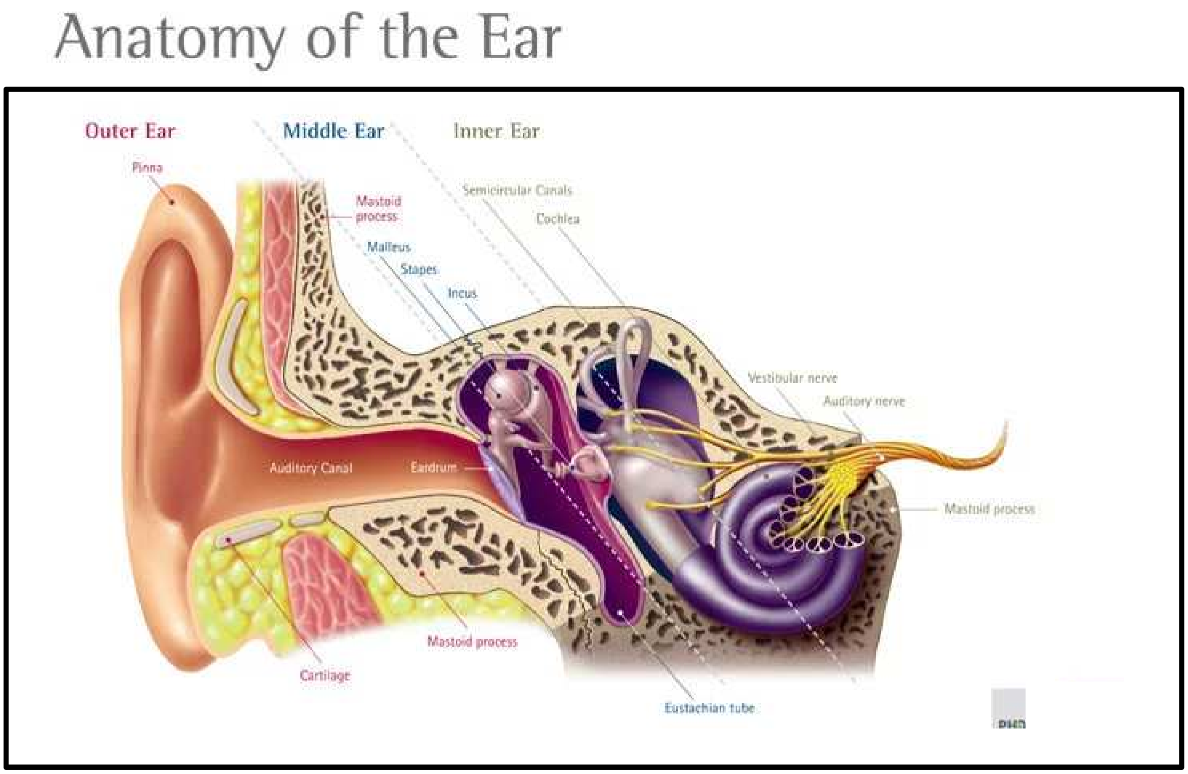
The reference sound pressure level is defined as the lowest sound pressure level that is able to be detected by the human ear (Stieger et al., 2018).

Auditory System

The auditory system is composed of the peripheral auditory system and the central auditory system. Included within the peripheral auditory system are the outer (external) ear, the middle ear, the internal ear (cochlea), and the auditory nerve. The external ear consists of the auricle (ear) and the auditory meatus (ear canal). The middle ear is made up of ear drum, ossicular chain, Eustachian tube, tendons, muscles, and a branch of the facial nerve. The main purpose of the middle ear is to increase the acoustic energy from the external ear to the cochlea. The cochlea (internal ear) contains stereocilia (hair cells) within its organ of Corti. As acoustic energy enters the organ of Corti, these hair cells vibrate and change acoustic energy to electrochemical energy that is then carried by the auditory nerve from the cochlea to the brainstem and temporal lobe of the brain (Levy & Wegman, 2000; Musiek & Baran, 2018).

Figure 3

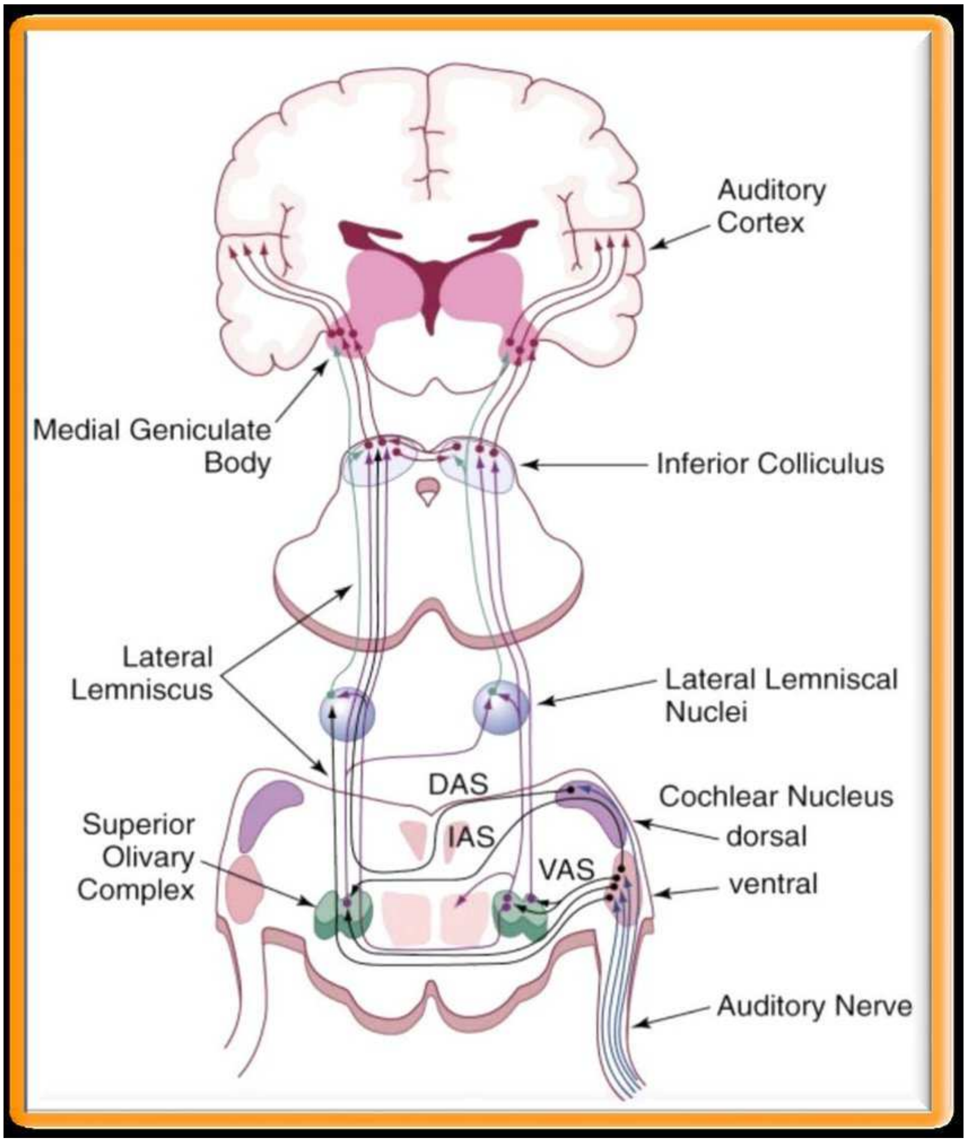
Peripheral Auditory System



The central auditory system is primarily located within the brain and consists of the cochlear nucleus, superior olivary complex, lateral lemniscus, inferior colliculus, medial geniculate body, auditory subcortex, cortex, and interhemispheric pathways. The auditory nerve carries information from the peripheral auditory system to the central auditory nuclei. The majority of this information is transmitted via crossing fibers into the superior olivary complex, where it continues through the contralateral side of the brainstem to the cortex. It is within the brain cortex that the processing of auditory information occurs (Peterson, Reddy, & Hamel, 2020).

Figure 4

Central Auditory System



Noise Induced Hearing Loss

The high frequency range of hearing is generally the first area to be affected by noise induced hearing loss. This is evidenced by a characteristic "notch" at approximately

4 kHz. In other words, the audiogram shows poorer hearing at 4 kHz than at both lower and higher frequencies. As NIHL progresses, the person may have difficulty in all listening environments. This can affect their social lives as well as their occupational abilities, sometimes impacting employability. From the United States government point of view, the financial impact can be enormous. During the years 1970 through 1990, the U.S. Veterans Administration paid approximately $24 billion dollars in hearing loss compensation (Wolgemuth, Luttrell, Kamhi, & Wark, 1995). A related consequence of noise exposure is noise induced tinnitus and it, too, can affect both social and work lives (Henry, Dennis, & Schechter, 2005). The world-wide social and financial impact of military, industrial, and recreational noise exposure is enormous.

In general, acoustic stimulation deflects the hair bundles on top of the hair cells in the cochlear. The stereocilia's' mechanoelectrical transduction channels can open when the shear forces stretch tip links between adjacent hairs. The opening of these channels results in excitation by ion influx into the cell which depolarizes the plasma membrane. This depolarization causes neurotransmitter release, sending a signal to the brain regarding the noise exposure. The channels are closed as a result of shear forces in the opposite direction (Roberts, Howard, & Hudspeth, 1988; Saunders, Cohen, & Szymko, 1991). Noise exposure can also temporarily decrease cochlear microcirculation and this reduction in blood flow has been associated with hearing loss (Henderson, Subramaniam, & Boettcher, 1993; Miller et al., 1996; Quirk, Avinash, Nuttall, & Miller, 1992; Vertes, Axelsson, & Lipscomb, 1979; Vertes, Axelsson, Miller, & Liden, 1981).

A variety of cochlear anatomical changes occur when the ear is exposed to excessive noise exposure. It is well known that excessive noise exposure results in outer hair cell loss and, to a lesser extent, inner hair cell loss, mostly in the basil portion of the cochlea (Henderson & Hamernik, 1995). It has been reported that degenerated hair cells will eventually be replaced by phalangeal scars, but one to two hours after noise exposure, holes in the reticular lamina may be present where the hair cells were, and this could allow for endolymph infiltration (Bohne & Rabbitt, 1983). Subsequent degeneration of supporting cells, nerve fibers and possibly sensory cells may then occur. Importantly, in addition to the actual loss of cochlear hair cells, more subtle forms of hair damage may occur including swelling and vacuolization of the hair cells, swelling of the supporting cells, fractures or discontinuities of the stereocilia rootlets, splaying of the stereocilia, deterioration of the stereocilia shafts' actin crystals and loss of tip links (Engström, 1983; Lim, 1986; Slepecky, 1986; Thorne, Duncan, & Gavin, 1986).

Hearing loss can be induced through excessive noise by either mechanically over-stimulating the cochlea or by metabolic processes. When noise exposures are under 125 dB SPL, most damage to the cochlear is a result of metabolic processes (Henderson & Hamernik, 1995). When sound noise levels reach or exceed 125 dB SPL, in addition to the metabolic damage, there is also mechanical damage (Henderson & Hamernik, 1995). For both impulse noise and continuous noise in excess of 125 dB SPL, where both metabolic and mechanical damage can occur, protective pharmacologic agents have shown promise in reducing noise induced hearing loss. Antioxidants have been shown to reduce hearing threshold shifts as well as reduction in outer hair cell loss. It has been reported NAC and acetyl-L-carnitine (ALCAR) offer protection (Kopke et al., 2004; Kopke et al., 2000). Other studies have shown D-methionine (D-met) to offer cochlear protection from continuous noise (Kopke, Coleman, Liu, Campbell, & Riffenburgh, 2002).

Occupational Noise Induced Hearing Loss

NIHL has been, and continues to be, one of the most reported occupational diseases throughout the world and it is seen across a large spectrum of industries (Lie et al., 2017; Mirza & Kirchner, 2018). In general terms, occupational NIHL is acquired hearing loss due to cell damage in the peripheral auditory system as a result of workplace exposure (Krishnamurti, 2009; Kujawa & Liberman, 2009; Steyger, 2009). There is no accepted objective definition for determination of occupational NIHL (Morris, 2019) however there are different guidelines that aid in the determination of occupational NIHL. Spoken communication occurs in frequencies between 500 Hz and 4,000 Hz, thus some definitions of occupational NIHL place larger emphasis on being able to hear sound in this frequency range. As noise exposure affects hearing in the 3,000 to 6,000 Hz range with greater veracity, other definitions of occupational NIHL focus on this higher frequency range (Lie, Engdahl, Hoffman, Li, & Tambs, 2017).

Occupational NIHL is a function of both intermittent and continuous noise exposure. This hearing loss is always sensorineural, as it affects the hair cells within the cochlea, and progresses slowly over time. Diagnosis is typically made by an Occupational & Environmental Medicine physician. The initial indication of occupational NIHL is a “notch” in the audiogram in the range of 3,000 to 6,000 Hz with recovery at

8,000 Hz (Mirza & Kirchner, 2018). It has been reported that occupational NIHL due to continued exposure increases most rapidly over the initial ten to fifteen years and this rate of hearing loss decreases with increasing hearing threshold levels (Mirza & Kirchner, 2018).

It is believed that occupational NIHL is a preventable disease that can be mitigated through a variety of controls. Engineering controls can be implemented to reduce the sound level reaching employees. Administrative controls can be put in place to reduce the cumulative noise level to which employees are exposed over the course of each workday. Additionally, personal protective equipment can be used to reduce the sound level reaching the ears of employees (Mirza & Kirchner, 2018). As a result, governmental regulations have been put into place to try and reduce, if not eliminate, occupational NIHL.

Hearing Loss Prevention in the Workplace / OSHA Regulation

In part, to try and prevent occupational NIHL, in 1970 the United States government passed the Occupational Safety and Health Act. This act created a legal structure to protect people in the United States workforce from hazardous working conditions. A direct result of this act being put into law was that OSHA and NIOSH created occupational noise exposure recommendations and standards, albeit not identical in their definitions.

Starting in 1969, OSHA created regulations that initially only covered workers in the manufacturing sector even though many other sectors had high noise exposures (Dobie, 1982). To their credit, OSHA modified its regulations to include essentially all occupations. OSHA currently mandates the incorporation of a hearing conservation program for work sites with excessive noise levels, defined as an 8-hour TWA noise level of 85 dB. The hearing conservation program must include the following program elements (Berger, 2003):

1. **Noise surveys and data analysis** to measure workplace noise levels and monitor worker noise exposure levels in order to identify areas of high noise exposure,
2. **Education** of workers about occupational noise hazard and the use of the hearing conservation program to prevent occupational NIHL,
3. **Noise control** using engineering and administrative controls to eliminate or reduce hazardous occupational noise exposures,
4. **Hearing protection devices** that can be worn to protect workers from being exposed to excessive noise, and
5. **Audiometric monitoring** of workers' hearing to detect significant hearing loss and governmental reporting of significant hearing threshold changes among those workers in their hearing protection program.

The OSHA standard defines the maximum allowable noise exposure as 90 dB over an 8-hour period, in other words, a TWA of 90 dB. Included in the OSHA standard is a 5 dB exchange rate that allows workers to be exposed to noise levels greater than 90 dB for shorter durations. The exchange rate is the dB change that results in a doubling (or halving) of the TWA value. As an example, utilizing the 5 dB exchange rate, a worker exposed to 95 dB for 4 hours has equivalent noise exposure to a worker exposed to 90 dB for 8 hours (OSHA, 1983). It is interesting to note that NIOSH recommendations, which are not enforceable by law, utilize a 3 dB exchange rate (Roberts, Seixas, Mukherjee, & Neitzel, 2018) which is the value that physics dictates. Use of the 3 dB exchange rate would result in workers spending less time in work areas where the noise exposure is greater than 90 dB.

As part of the audiometric portion of the hearing conservation program, OSHA mandates that employers monitor their workers' hearing threshold shifts over time. Each employee entering a work site at which noise is at or above an 8-hour TWA of 85 dB must undergo audiometry within six months to obtain a baseline audiogram. Each of these employees must then undergo annual audiometric testing to determine if they have experienced a standard [hearing] threshold shift. If the standard threshold shift is verified through a re-test, then the employee is recorded as having experienced a standard threshold shift and their baseline audiogram can be substituted with this most recent audiogram (OSHA, 1983).

Occupational Hearing Loss

Occupational hearing loss continues to be a significant problem. However, not all workers subjected to comparable noise exposures experience similar levels of hearing loss. A longitudinal, retrospective cohort study of 10,567 U.S. Air Force aviation-related personnel was conducted to determine factors associated with an occupationally significant change in hearing sensitivity (Greenwell, Tvaryanas, & Maupin, 2018). Occupationally significant change in hearing sensitivity was evaluated using the first occurrence of a significant threshold shift in an individual's audiogram. The definition utilized for a significant threshold shift was that defined by OSHA, namely, a change in hearing from baseline of at least 10 dB among the average hearing thresholds of 2000, 3000, and 4000 Hz in at least one ear. The results of statistical modelling revealed that after controlling for subject age, duration of time in the cohort after baseline audiogram, and gender, there were large variations in the probability of a significant threshold shift among subjects in the same Air Force Specialty code (which are jobs that are grouped together as having similar occupational exposures due to working in the same type of aircraft). This is evidenced by the large standard errors associated with the estimate for each Air Force Specialty code relative to the estimate value. For example, the parameter estimate for Aircraft loadmasters was -0.446 with a standard error of 1.106. Thus, the standard error is over twice that of the parameter estimate. And, based upon a gaussian distribution, 95% of the population would fall between -1.96 standard deviations and +1.96 standard deviations of the parameter estimate. Thus, there is a very large variability in the probability of a significant hearing shift among Aircraft loadmasters after accounting for subject age, duration of time in the cohort after baseline audiogram, and gender. This was not unique to Aircraft loadmasters. Airborne mission system subjects had a parameter estimate of -0.840 with a standard error of 1.370 while Airlift pilots had a parameter estimate of -0.253 with a standard error of 0.493. The authors also noted that less than 25% of the variability in hearing sensitivity was explainable with the factors included in the analysis. Thus, controlling for these factors known to be associated with noise induced hearing loss, there was much more unexplained variation than explained variation in determining the likelihood of a significant threshold shift.

A prospective, randomized, double-blinded, placebo-controlled clinical trial involving 566 subjects was conducted to determine the safety profile and efficacy of the antioxidant NAC in preventing NIHL within a military population undergoing weapons training (Kopke et al., 2015). The study was a conducted because there continues to be a high risk for NIH among military personnel despite having a robust hearing conservation program. The cohort used for the study consisted of volunteers aged 18 to 35 years that were recruited from trainees at the U.S. Marine Corps Recruit Depot in San Diego, California. Study subjects were randomized into either the active (received NAC) or the placebo arm of the study. The subjects initially underwent audiometric hearing threshold testing to determine their baseline prior to weapons training which occurred throughout a 16-day training period, the last three days of which simulated war. A final audiometric threshold hearing test was given to each subject approximately two weeks after completion of their weapons training. Of the 289 subjects that were randomized to the placebo group, 38.4% experienced a significant threshold shift in at least one of their ears. A significant threshold shift was defined as an increase of at least 20 dB at any tested frequency or an average increase of at least 10 dB at any two consecutively tested frequencies. For this study, the test frequencies consisted of 2000, 3000, 4000, 6000, 8000, 10000, 12500, 14000, 16000, 18000, and 20000 Hz. Approximately two-thirds of the subjects in the placebo arm of the study did not experience a significant threshold shift. Examining subjects in the placebo arm regarding a significant threshold shift in both ears, it was found that 7.6% of these subjects experienced a significant threshold shift in both ears. Therefore, 92.4% did not experience this type of hearing loss.

Experiencing a significant threshold shift (or not), by definition, is a binary outcome. The authors also analyzed threshold hearing loss on a continuous basis by subtracting each subject's baseline hearing threshold level from their final hearing threshold level, separately for each tested frequency. Thus, the change in volume, in dB, required to hear each tested frequency was determined. In general, the mean change in hearing among the subjects in the placebo arm of the study was less than 1 dB. However, the standard deviation of the change in threshold hearing level varied between 5.1 dB and 11.4 dB depending upon the tested frequency. This study revealed that there is large variability in both the probability of a significant hearing shift and in the change in hearing threshold level among military recruits.

Another prospective, randomized, double-blinded, placebo-controlled clinical trial involving 252 subjects was conducted to determine the safety profile and efficacy of the antioxidant D-Methionine in preventing NIHL within a military population undergoing weapons training (Campbell, 2016). The cohort used for the study consisted of Drill Sergeant School Instructor candidates undergoing training at Fort Jackson, South Carolina. Study subjects were randomized into either the active (received D-Methionine) or the placebo arm of the study. The subjects initially underwent audiometric hearing threshold testing to determine their baseline audiometric hearing thresholds prior to their weapons training, an integral part of their drill sergeant training. A final audiometric threshold hearing test was given to each subject approximately two weeks after completion of their weapons training. Of the 289 subjects that were randomized to the placebo group, 14.7% experienced a significant threshold shift in at least one of their ears. A significant threshold shift was defined as an increase of at least 20 dB at any tested frequency or an average increase of at least 10 dB at any two consecutively tested frequencies, or a loss of response in three consecutive frequencies for which responses were obtained at baseline. For this study, the tested frequencies consisted of 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz. Approximately six in seven subjects in the placebo arm of the study did not experience a significant threshold shift. The authors also analyzed threshold hearing loss on a continuous basis by subtracting each subject's baseline hearing threshold level from their final hearing threshold level, separately for each tested frequency. Thus, the change in volume, in dB, required to hear each tested frequency was determined. In general, the mean change in hearing among the subjects in the placebo arm of the study was less than 1 dB. However, the standard deviation of in the change in threshold hearing level varied between 3.4 dB and 7.6 dB depending upon the tested frequency. Like the previous study, this study also revealed that there is large variability in both the probability of a significant hearing shift and in the change in hearing threshold level among military recruits.

The non-military sector also shows heterogeneity with regard to hearing loss. One study (Masterson, Themann, & Calvert, 2018) describes the prevalence of hearing loss, by job types, among noise exposed workers within the healthcare and social assistance sector. Although the goal of this study was to understand which job types had the greatest risk for NIHL, the published data was able to reveal the true variability within job types. For instance, 31.49% of medical and diagnostic laboratory workers were shown to have hearing loss as defined by the NIOSH definition of impairment: an average hearing threshold of at least 25 dB averaged across 1000, 2000, 3000 and 4000 Hz. Therefore two-thirds of medical and diagnostic laboratory workers did not have hearing impairment. The authors note that 17.72% of individuals working in physicians' offices had a hearing impairment, that means that 82.28% of these workers did not having hearing impairment. As was observed within the military sector, there is evidence of great variability in an individual's susceptibility to NIHL.

A series of meta-analyses have been published to understand the association between various genetic polymorphisms and susceptibility to NIHL. Lei et al., 2017 revealed a significant association between certain polymorphisms of heat-shock protein 70 (HSP70) encoding genes and NIHL. The authors found that rs1061581 and rs2227956 polymorphisms were significantly associated with NIHL among male Caucasians. Wang et al., 2017 found evidence that the C47T polymorphism in superoxide dismutase gene 2 was associated with increased propensity for NIHL in the Chinese population. Xin Li et al., 2020 found that there was a significant association between rs3735715 polymorphism in the GRHL2 gene and susceptibility to NIHL. Lastly, a case-control study to determine if there was an association between PON2 and ATP2B2 gene polymorphisms and NIHL was conducted by Li et al., 2016. This research revealed that PON2 may play a role in the etiology of NIHL among Chinese of Han nationality. Together, these studies suggest that there is a genetic component that modulates an individual's risk for NIHL. Genetic differences between individuals would add to the variability observed among individual responses to noise.

Summary and Rationale for Study

It is clear that there are individuals that have greater susceptibility to occupational NIHL. This was described seventy years ago in a seminal article by Wheeler on the subject (Wheeler, 1950). The author went on to say that at the time, it was not possible to determine in advance which individuals would experience hearing loss due to exposure to noise. The author felt that there was a need for development of testing which could differentiate those susceptible to NIHL prior to placing that person in a noisy occupational setting. Wheeler noted that it might not be possible to develop such a test and therefore a somewhat less attractive alternative would be to retest employees after sustaining a period of occupational noise exposure. Today, seventy years later, we have identified factors associated with propensity for NIHL, but even after adjusting for these factors, there remains large variability in individual response to noise exposure and those individuals with a propensity for experiencing NIHL are still unable to be identified prior to being placed in a noisy occupational setting.

The required use of serial audiograms and reporting of significant threshold shifts in hearing, a requirement set by OSHA, was a step toward the less attractive alternative noted by Wheeler. By the time individuals experience significant threshold shifts, they have already lost a fair amount of hearing. Realizing that the ability to differentiate individuals more susceptible to NIHL prior to being placed into a noisy occupational environment does not currently exist, the ability to determine susceptible individuals early in their occupational career would be extremely helpful as it could mitigate NIHL even among susceptible persons. In the next section, Chapter 3, the research design and methodology used in this research will be described.

Chapter 3: Research Design and Methods

This chapter provides both the purpose of this research and the methodology used to conduct the study. The study design used for this research, as well as the reasoning behind that choice, is discussed. The specifics regarding how I collected and obtained the data are detailed. The statistical methodology used for data analysis, along with the assumptions that are intrinsic to the methodology, are presented. Lastly, the consideration of potential ethical issues is discussed.

Purpose of the Study

The purpose of this study was to determine the underlying factors predisposing people to NIHL as well as the association between early occupational hearing loss and future occupational hearing loss. To address this gap in knowledge, NIHL was defined using a noise notch criterion, as NIHL is characterized by a loss of hearing in the mid-frequencies with lesser loss at the extremes of the measured audiometric test frequencies. A quantitative research approach was used to determine the demographic, occupational (including early career hearing loss), and lifestyle factors that are associated with noise induced hearing loss along with their effect sizes.

Research Design and Approach

As part of their day-to-day operations, corporations create and maintain large databases. Each of these databases are typically developed and used by specific organizations within the corporation. My dissertation used some of this existing data that had been collected on United States employees of a large multinational manufacturing corporation. Specifically, I analyzed data from four of the corporation's datasets.

The corporation's hearing conservation program requires noise-exposed employees to undergo pure tone audiometric hearing threshold tests on an annual basis. The results of these audiometric tests are stored electronically in their occupational health management (OHM) dataset. The OHM dataset contains longitudinal audiometric data on tens of thousands of employees and covers tests conducted for over 2 decades. Included within this data set are individual records that contain the employee number, the date of the audiometric test, and the sound amplitude, in decibels, required to hear each of the tested frequencies in each ear. As noise exposed employees will typically have many hearing tests over their career, this data set contains repeated measures of hearing, by individual, over time.

In order to keep track of the people employed by their corporation, information regarding each employee is maintained in their human resources data set. This data set contains demographic data as well as occupational information for each employee. Each time that there is a change in the employee's information, a new record is added to the data set. Thus, there are many records in the data set for each employee which allows one to determine their status at any point during the time period that they were employed by the corporation.

As part of compliance with OSHA regulations, the corporation must assess employee exposure to various toxicological agents. For those jobs where there is potential for exposure, industrial hygiene measurements are taken to determine the TWA exposure levels. For each agent and job combination measurement, a record is created in the industrial hygiene data set. The actual measured value, time duration of the measurement, agent assessed, and date of the measurement are recorded. Thus, for each agent, the history of job exposures can be reconstructed.

This corporation, as is relatively common with large United States corporations, is self-insured with regard to employee's medical insurance. Through its third-party administrator, all medical claims, by individual, are captured in the medical claims database. The practical reason for this is that health care providers need to provide certain information, such as the identity of the person seeking health care, the date of the encounter, and the ICD-9 or CPT code for the visit to be reimbursed. Fortunately, this corporation provided good benefit plans at minimal cost to the employees, so almost all employees opted into the medical plan. This mitigated any potential selection bias issues.

Using the information contained in each of these independent data sets, various time dependent factors can be calculated. The human resources data set allows for the determination of job history by employee. Linking the industrial hygiene data set information regarding job exposures will allow each employee's exposure history to be determined. At any point in time that an employee undergoes audiometric testing, their cumulative exposure (including cumulative noise exposure) will be known. The information contained within the medical claims data set allows for determination of disease status, and in particular chronic disease status, at any given time during each employee's tenure. Additionally, for all audiometric tests after the employee's initial hearing test, the change in threshold hearing will be available.

The following information contained within the four aforementioned data sets was made available for the research study:

1. OHM data set: This data set contains all audiometric data as well as certain biometric information including body mass index (BMI) and smoking history. The audiometric data has the threshold hearing level for each frequency (500 Hz – 8,000 Hz) for each ear by person and date,
2. Human Resources data set: This data set contains demographic data including age, gender, and race as well as occupational data including hire date, job title, and the date the job became effective. Separate records are created for each change in job as well as for any other significant changes in information,
3. Industrial Hygiene data set: This contains information on measured job exposures for various agents including noise, and
4. Medical Claims data set: Among other items, this data set includes date of service, diagnosis code (ICD-9), and procedure code (CPT). It should be noted that algorithms utilizing the longitudinal nature of claims data have been developed (Cullen et al., 2006), allowing for determination of incidence date for chronic diseases including, but not limited to, diabetes.

Prior to my obtaining it, each data set was de-identified using an algorithm that allowed the data to remain linkable by individual to records both within the data set as well as across the four data sets maintained by the corporation. Finally, the corporation had agreed to make this data available to me once there was IRB approval from Walden University for the study.

There were no inclusion criteria regarding age, as noise induced hearing loss can occur at any point during a person's lifetime. The corporation has very few, if any, employees below the age of 18 years. Additionally, they will have very few over the age of 70 due to their retirement benefits. Lastly, there was little to no likelihood of an employee being significantly cognitively impaired, as they must be able to function on a daily basis in a supervised work setting.

The overall statistical approach used the longitudinal nature of the data given that each subject has had multiple audiometric tests performed with the results of each test recorded. A noise notch definition was used as the operational definition for hearing level. The one used for this study incorporated components of the Coles notch criteria (Coles et al., 2000), the Niskar notch criteria (Niskar et al., 2001), and the notch index (Rabinowitz et al., 2006). For this study, the operational definition for hearing level was the difference between the pure tone average of thresholds at 2, 3, and 4 kHz and the average of thresholds at 1 and 8 kHz in the same ear. Mathematically, this is expressed as:

$$HL[dB] = ((HTL_{2k} + HTL_{3k} + HTL_{4k}) / 3) - ((HTL_{1k} + HTL_{8k}) / 2)$$

where:

HL = Hearing level

HTL_{fk} = Audiometric threshold hearing level at frequency, fk.

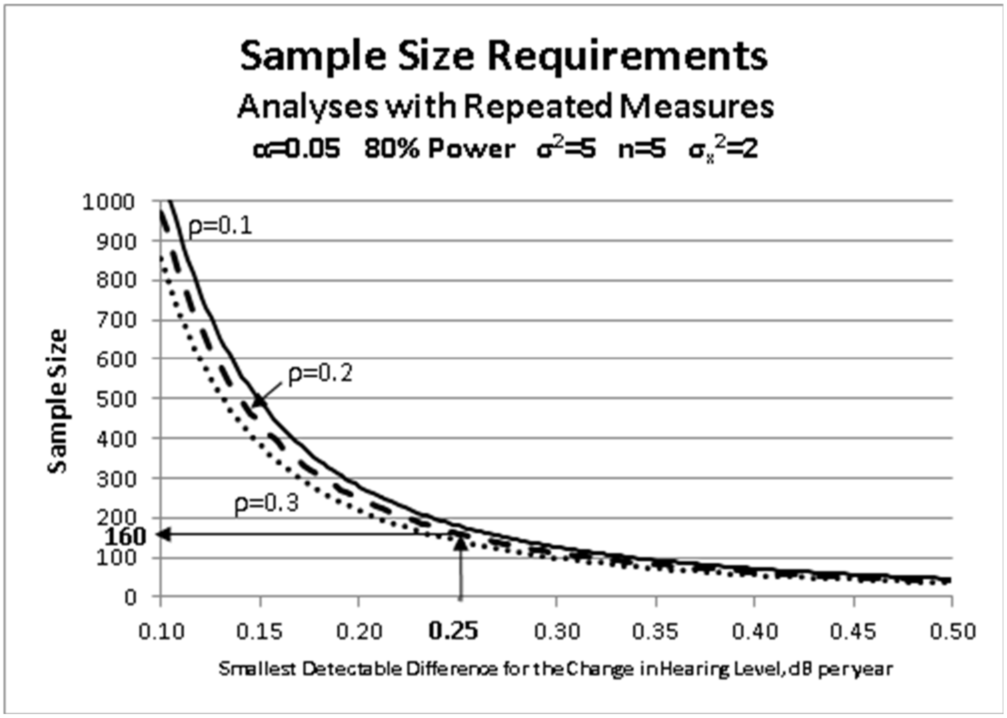
Based on this definition, if the pure tone average of thresholds at 2, 3, and 4 kHz is equal to the pure tone average of thresholds at 1 and 8 kHz, then the hearing level equals zero. When the pure tone average of thresholds at 2, 3, and 4 kHz is less than the pure tone average of thresholds at 1 and 8 kHz, then the hearing level will be less than zero. When the pure tone average of thresholds at 2, 3, and 4 kHz is greater than the pure tone average of thresholds at 1 and 8 kHz, then the hearing level will be greater than zero. This last case is indicative of noise induced hearing loss.

Sample Size

The required sample size was determined using the method described by Singer and Willett (2003). This methodology requires that the confidence level, power, variance of the outcome measure, the number of repeat measurements, the timing of these measurements, the correlation between measurements, and the smallest detectable difference be specified. To power my study, a significance level of 95% (α=0.05), 80% power, a variance in threshold hearing of 5 dB and 5 repeated measurements, each taken one year apart, were defined. Additionally, various correlations and smallest detectable differences were specified in order to understand the sensitivity of the required sample size for these parameters. The required sample size for these specifications is depicted in Figure 5.

Figure 5

Sample Size Requirements



From the figure, it can be observed that 160 subjects will be sufficient to detect a difference in the change in hearing level of 0.25 dB/year. As the corporation's data sets include data on literally thousands of employees, the study had sufficient power to detect this difference even after accounting for the split sample nature of the methodological approach.

Instrumentation and Materials

The corporation has used the OHM medical records database to store audiometric data obtained from its employees. As per the corporation's health and safety protocols, employees in jobs for which the 95th percentile of 8-hour TWA measured noise exposures is at least 85 dBA must have yearly surveillance audiometry. Employees in jobs with 8-hour TWA measured noise exposures of at least 82 dBA but less than 85 dBA must undergo audiometric testing at least every 3 years (Rabinowitz et al., 2008). Audiometric testing is performed under the supervision of the corporation's chief medical officer in hearing booths or trailers that are recertified each year (Donoghue et al, 2016). The audiometric testing included pure tone threshold hearing levels at seven frequencies (500 Hz, 1k Hz, 2k Hz, 3k Hz, 4k Hz, 6k Hz, and 8k Hz) measured separately in each ear. Thus, a total of 14 measurements were recorded during each hearing test. Also recorded was the date and time of the test. With regard to hearing, the OHM data set included the date of the audiometric test, the results of the 14 separate threshold hearing levels, as well as the type of test (e.g., pre-placement, routine, exit audiogram). A complete listing of the variables associated with audiometry included in the OHM data set are included as Appendix A.

To manage their industrial hygiene risk assessment process, the corporation developed its own computer software. This application, HyGenius, maintained an electronic database that included information on all measured job exposures, including noise, dating back to 1985 (Rabinowitz et al., 2008). Included within the HyGenius database are the date of the sampling, the plant, the department and job at which the sample was taken, the agent that was sampled, the type of sample (e.g., personal TWA sample, area sample, personal peak sample), and the sampling strategy (random, worst case, or diagnostic). A complete listing of the variables included in the HyGenius data set are included as Appendix B.

The human resources department of the corporation used the commercial software product, PeopleSoft, and later, PeopleView, to manage data associated with their employees. Each time an action was taken with regard to an employee, a new record was written to this data set. Included within this data was the date of the action, the action taken (e.g., new hire, job change within the organization, termination of employment), as well as the employee's sex, ethnicity, and date of birth (which was recoded to year of birth prior to being made available for this study) and employee identification number (which was de-identified prior to being made available for this study). A complete listing of the variables included in the PeopleSoft/PeopleView data set are included as Appendix C.

The corporation was a self-insured with regard to its employees' medical expenditures. It used a TPA to manage the system. Each time a medical claim was received from a health provider for a service, a new record was entered into the claims database. The record included the date of the activity, the ICD9 diagnosis code or the CPT code, the employee identification, and the relationship of the patient to the employee. In this study, we only used medical claim records where the relationship is "Self", that is, the patient was the employee and not one of the employee's family members. A complete listing of the variables included in the Medical Claims data set are included as Appendix D.

Reliability and Validity

No assessment of the reliability or the validity of the instruments used by the corporation are included as this was beyond the scope of this study. It is assumed that the instruments used by the corporation for obtaining the data associated with noise exposure and hearing threshold levels met the requirements of OSHA standards. OSHA standards specify the requirements with regard to the methodology, accuracy and repeatability for measuring agents in the workplace as well as the calibration and required accuracy and repeatability of audiometers used to obtain hearing thresholds. As the corporation falls under OSHA's umbrella, it is assumed that these standards were met.

Source of Original Data

The source for all of the data was the corporation's research data warehouse, which was housed at, and maintained by, the corporation. The data sets housed by the corporation were de-identified, but linkable. Thus, the PeopleSoft/PeopleView data set was able to be linked by individual to the OMH data set. This preserved the integrity of the data while maintaining the security of the individual.

Data Collection and Analysis

The study population was comprised of employee's that worked for the corporation between 1996 and 2014 and had at least six audiograms over at least a minimum of 6 years. Typically, this required the employee to have been in the corporations' hearing conservation program. Almost 5,000 employees met this criterion. The variables that were included in the study are depicted in Appendices A, B, C and D.

Statistical Analysis

Initially, descriptive statistics were calculated to define the study population. Proportional Hazards regression modeling was utilized in order to determine the effects of occupational and demographic factors as well the trajectory of hearing level over the first few years of employment on the subsequent risk of hearing impairment. Bivariate, full and parsimonious models were developed using a backward selection process with a level of significance set at α=0.05 to determine the parsimonious model. T-tests (Pearson and Adyanthaya, 1929) were used to determine statistical significance of each individual predictor.

To ascertain the effect of the demographic, lifestyle, and occupational factors on the risk of hearing impairment during an employee's job tenure, the proportional hazards model used the following hazard function:

$$\lambda(t) = \lambda_0(t)\ \exp\ \{\ \boldsymbol{\beta_1}*(\mathbf{L_{eq}})_i + \beta_2*(\text{Initial hearing})_i + \boldsymbol{\beta_3}*[(\textbf{Demographic})_i + \boldsymbol{\beta_4}*[(\textbf{Occupational})_i + \boldsymbol{\beta_5}*(\textbf{Lifestyle})_i\}$$

where:

$\lambda(t)$ = Hazard function for developing hearing loss,

$\lambda_0(t)$ = Baseline hazard for developing hearing loss,

t = Years since initial audiogram,

$\mathbf{L_{eq}}$ = A matrix of equivalent continuous sound pressure levels where equivalent continuous sound pressure level is a function of the time an employee spent in the TWA associated with each job,

Initial hearing = A subject's change in hearing level over their first five years of enrollment within the corporation's hearing conservation program

$$= \frac{d[(\frac{(\mathrm{HTL2k}\ + \mathrm{HTL3k} + \mathrm{HTL4k})}{3} - (\frac{(HTL1k + HTL8k)}{2}]}{dt}$$

HTL_{fk} = Audiometric threshold hearing level at frequency, fk,

Demographic = A matrix of demographic factors held by each subject,

Occupational = A matrix of occupational factors held by each subject,

Lifestyle = A matrix of lifestyle factors held by each subject, and

i = i^{th} subject.

Research Questions and Hypotheses

The following research questions, as well as hypotheses, were evaluated through the conduct of longitudinal analysis of information contained within the corporation's data sets. The following research questions along with directional hypotheses were developed to address gaps in the current state of knowledge regarding predictors of hearing impairment as a result of occupational NIHL in a manufacturing setting.

RQ1: Which demographic factors (age, gender, and race) are associated with probability of hearing impairment given similar noise exposure?

$DH1_1$: It is expected that older workers will be at increased risk of hearing impairment based upon their annual audiometric test results.

$DH1_2$: It is expected that males will be at increased risk of hearing impairment based upon their annual audiometric test results.

$DH1_3$: It is expected that African Americans will be at decreased risk of hearing impairment based upon their annual audiometric test results.

RQ2: Is tobacco use significantly associated with probability of hearing impairment given similar noise exposure?

DH2: It is expected that current smokers will be at increased risk of hearing impairment based upon their annual audiometric test results.

RQ3: Which health conditions factors (obesity and diabetes) are associated with probability of hearing impairment given similar noise exposure?

$DH3_1$: It is expected that obese workers, as compared to overweight workers, will be at increased risk of hearing impairment based upon their annual audiometric test results and that overweight worker, as compared to normal weight workers, will be at increased risk of hearing impairment based upon their annual audiometric test results.

$DH3_2$: It is expected that diabetic workers will be at increased risk of hearing impairment based upon their annual audiometric test results.

RQ4: Is there an association between hearing loss early in an individual's work history and increased probability of hearing impairment given similar noise exposure?

DH4: It is expected that workers that have greater hearing loss early in their work history will be at increased risk of hearing impairment based upon their annual audiometric test results.

RQ5: In a multivariate adjusted model, which demographic, lifestyle, and occupational (including early career hearing loss) factors are associated with hearing impairment given similar noise exposure and are there significant interactions between the factors?

Human Subjects Protection

Institutional Review Board (IRB) approval was obtained from Walden University prior to commencement of the study. The only risk to the study subjects is the remote chance that personal health information could be revealed, causing social or economic harm. To minimize this risk, the data sets obtained were de-identified prior to my receiving them. Direct identifiers were excluded and unique employee identifications were created to allow linkage between the data sets. Additionally, the transfer of data was via a secure file transfer protocol, meaning that the data was encrypted prior to being transferred and decrypted once I receive it. After the data was received, it was stored on a secure computer system that limits access to files through password protection and file walls. Lastly with regard to protection of human subjects, all reported data is in aggregate form so that a subject is not able to be identified.

Chapter 4: Results

The study was conducted to determine the underlying factors predisposing people to NIHL as well as the association between early occupational hearing loss and future occupational hearing loss. The study used existing data that was previously collected on United States employees of a large multinational manufacturing corporation between January 1, 1996 and December 31, 2014. The ecological model of health behaviors provided the theoretical foundation of the study.

The ecological model of health behaviors provides a framework to bring together behavioral, social, policy, and biological aspects of the human experience into an epidemiological study. Ecological models note that it takes both individual-level and policy/environmental-level interactions to obtain significant change in behavior. In this study, the biological aspect of interest is hearing loss associated with occupational noise exposure.

This study was designed to answer the research questions and directional hypotheses through a longitudinal analysis of the data obtained from the multinational manufacturing corporation. Statistical analyses were conducted using t-tests (Pearson and Adyanthaya, 1929), Pearson's chi-square tests (Pearson, 1900), and Cox's proportional hazards models (Cox, 1972). Statistical significance was set for a 95% level of confidence, i.e., $\alpha=0.05$. This chapter describes the characteristics of the study population and summarizes the results of the statistical analyses performed for the study.

Characteristics of Audiometric Data

The OHM database was a repository for the results of audiometric testing conducted by the corporation on its employees. During the period January 1, 1996 to December 31, 2014, there were 155,105 audiogram records in the OHM database for which the employee undergoing the audiometric testing was found to have a normal otoscopy exam result, that is, the ear canals did not have excessive cerumen, impacted cerumen, nor any other abnormality that would negate the results of the audiometric testing. Incomplete audiometric test results were excluded from the study. Audiometric test results were determined to be incomplete if it was missing the date of the audiometric test or was missing results for any of the required test frequencies of 0.5k, 1k, 2k, 3k, 4k, 6k, or 8k Hz. After removal of these incomplete records, there were data on a total of 49,236 audiometric tests.

Characteristics of the Industrial Hygiene Data

The Industrial Hygiene database was a repository for the results of environmental testing conducted by the corporation at its various job locations. Among the agents for which testing was conducted, the one of interest for this study was noise level. There were 27,763 measurements of noise using random, personal sampling in which the measurement was deemed valid by the corporation's industrial hygienist.

Study Population

The study population included 4,894 subjects that had at least six audiograms. They were predominantly White (82.75%) and male (90.54%). At the start of the study period, they ranged from 17 to 69 years of age with a mean age of 41.21 (SD=8.93

years). Relatively few of the subjects were current smokers (8.64%) at the start of the study period, while a large percentage of them where either overweight (37.54%) or obese (40.72%). Additionally, 19.27% of the subjects were diabetic at the start of the study period. Further information regarding these characteristics is depicted in Table 2.

Table 2

Characteristics of Study Population

Characteristic	n	%
Age group		
17-29	683	13.96
30-39	1,311	26.79
40-49	2,058	42.05
50-59	817	16.69
60-69	25	0.51
Gender		
Female	463	9.46
Male	4,431	90.54
Race/ethnicity		
Black	528	10.79
White	4,050	82.75
Hispanic	256	5.23
Other	60	1.23
Smoking status		
Current	423	8.64
Former	1,807	36.92
Never	1,822	37.23
Unknown	842	17.20
BMI class		
Normal	622	12.70
Overweight	1,837	37.54
Obese	1,993	40.72
Unknown	442	9.03
Diabetes		
Yes	943	19.27
No	3,951	80.73

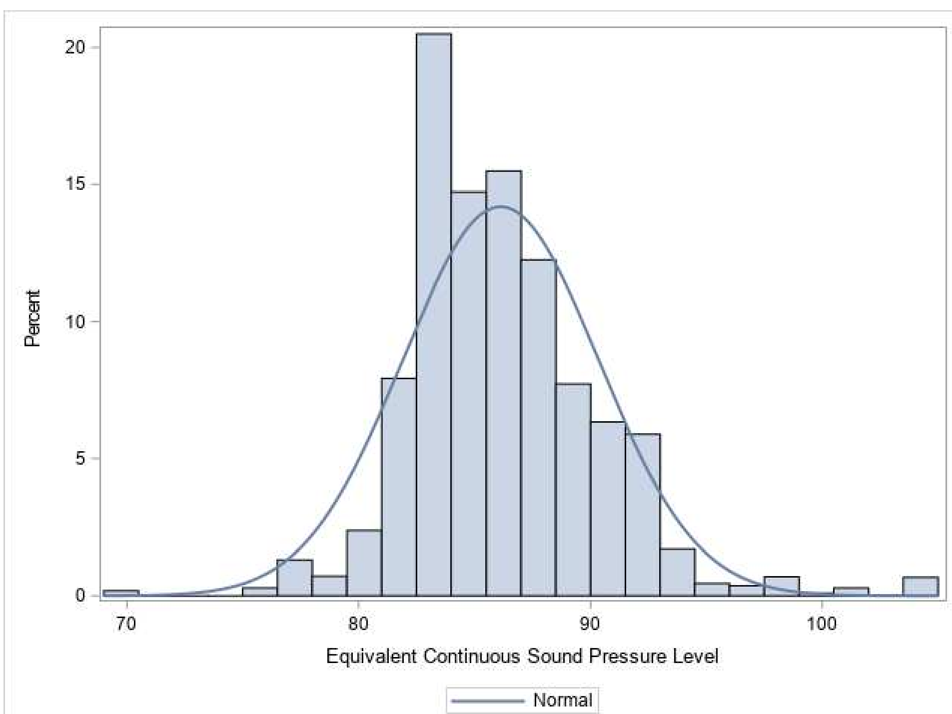
Note. N = 4,894

Noise Exposure

Jobs were grouped into similar exposure groups (SEGs) by the corporation's industrial hygienists that were knowledgeable about the environment and exposures for the jobs. All noise measurements obtained from a job within a given SEG were used to determine the mean noise exposure for that SEG (and, therefore, for each job within that SEG). Each subject's equivalent continuous sound pressure level (Leq) was then calculated based upon their job history during the period of the study. Individual Leq levels ranged from 69.04 dB to 104.78 dB with a mean Leq of 86.12 dB (SD=4.21 dB). The distribution of Leq during the study period is depicted in Figure 6.

Figure 6

Distribution of Equivalent Continuous Sound Pressure Level (Leq) During the Early Period of Audiometry Testing



Early Hearing Loss

Early hearing loss was determined from audiogram test results from a subject's first 5 years of testing. To be included in the study, the subject was required to have had at least three audiograms during this period. The average number of audiograms on a subject during this period was 4.82 (SD=1.21), with the distribution depicted in Figure 7. Early hearing loss was defined as the slope of the calculated noise notch. The slope of the noise notch ranged from -3.58 dB/year to 4.17 dB/year with a mean slope of 0.26 dB/year (SD=0.78 dB/year). The distribution of the slope of the noise notch during the early hearing loss period is depicted in Figure 8.

Figure 7

Distribution of the Number of Early Period Audiograms per Subject

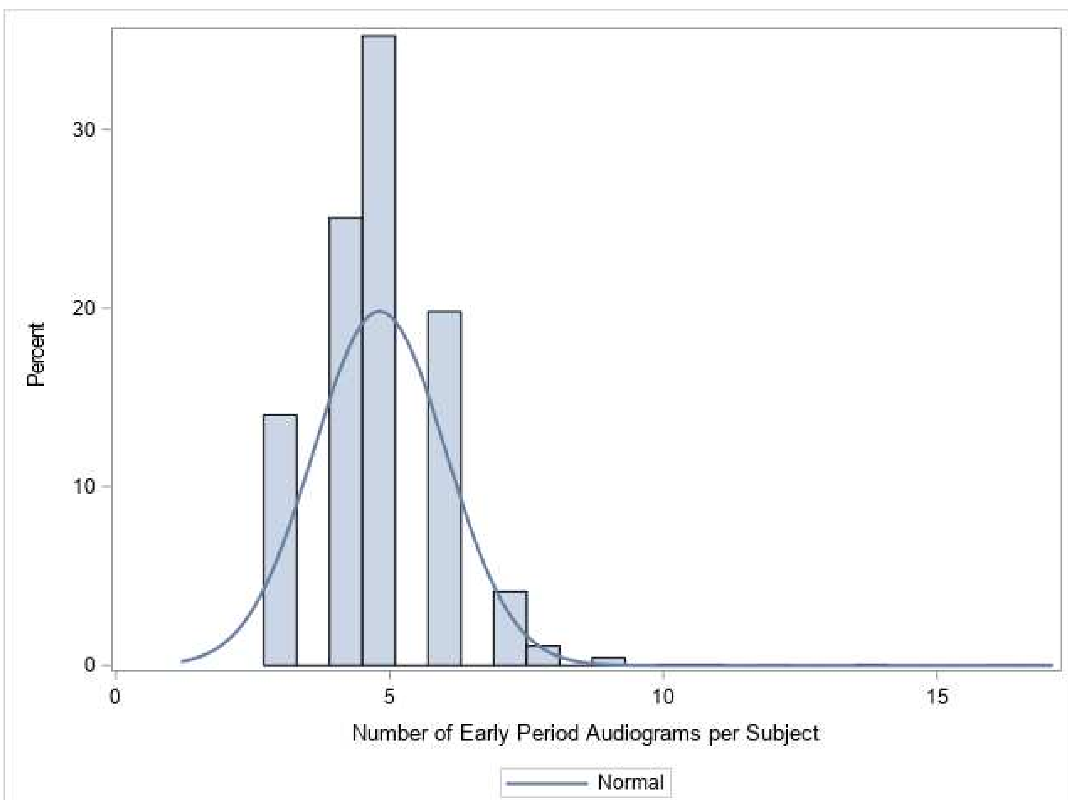
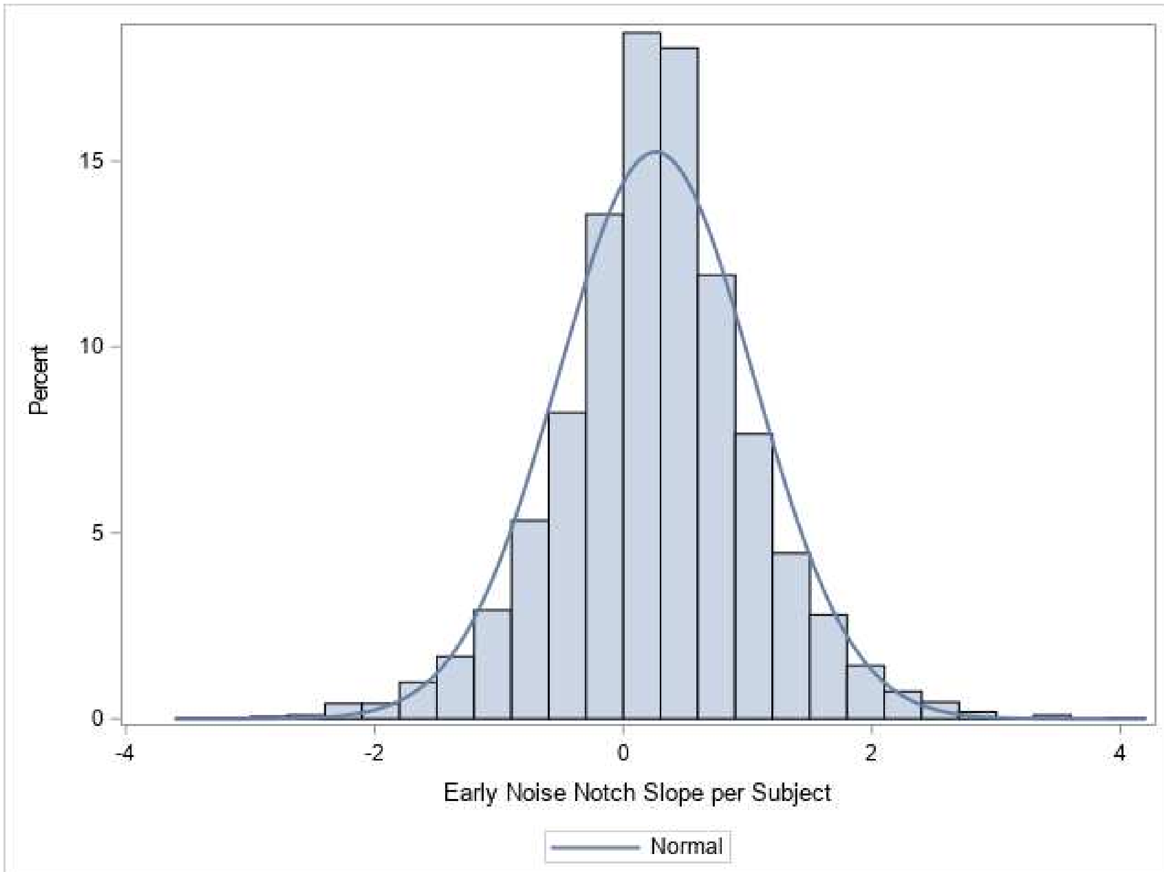


Figure 8

Distribution of Noise Notch Slope During Early Period of Audiometry Testing



Hearing Impairment

As previously noted, hearing impairment was defined using the American Medical Association criteria as an average hearing threshold in either ear from the frequencies of 500, 1k, 2k, and 3k Hz that exceeded 25 dB. The average time of follow-up for the study population was 5.69 years (SD=3.21 years) with a range from 0.01 years to 13.24 years. Among the 4,894 study subjects, 708 (14.47%) developed hearing impairment during the study period.

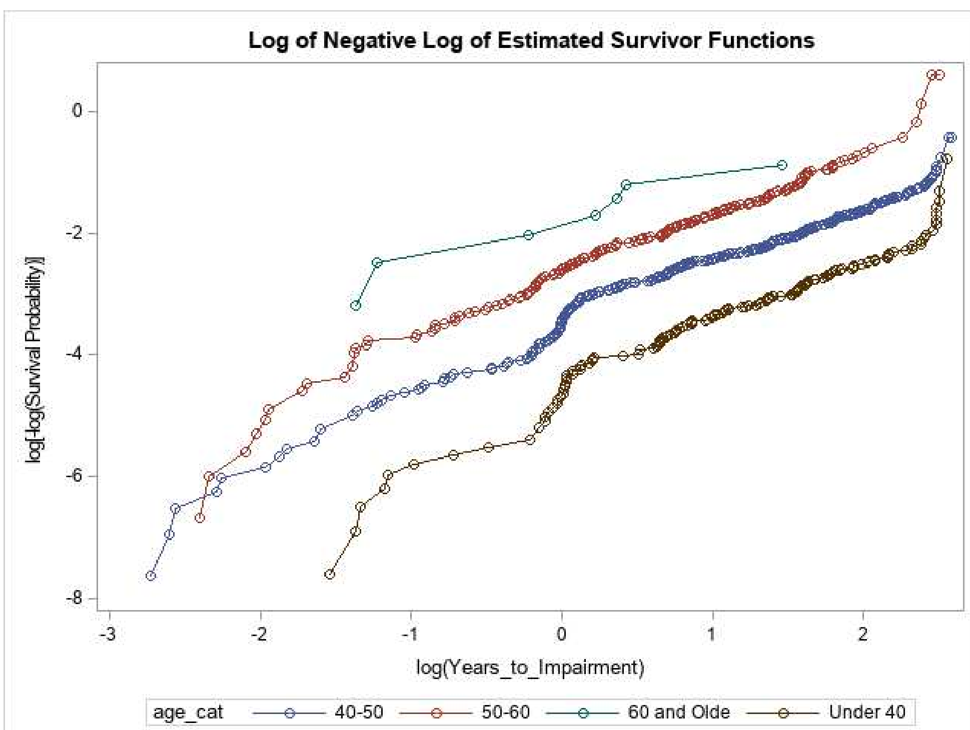
Research Question 1

The first research question was developed to determine the risk of developing hearing impairment for workers enrolled in the corporation's hearing conservation program by age, gender, and race as measured by annual audiometry testing. Directional hypothesis 1a predicted that older workers would be at greater risk of developing hearing impairment than younger workers as measured by annual audiometry testing.

Initially, to determine if the assumption of proportional hazards was met, a plot of log(-log(survival)) vs. log (years to impairment) was created (Figure 9). As can be observed from the figure, the slopes of the various age categories are relatively parallel, thus there is no evidence to dismiss the assumption of proportional hazards.

Figure 9

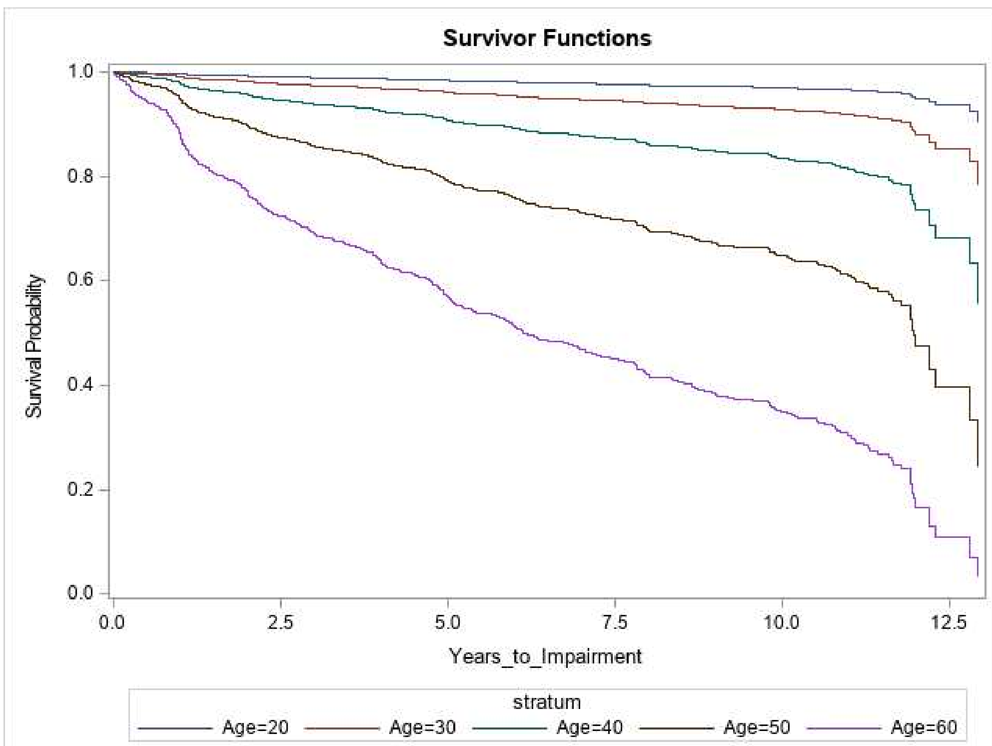
Log(-Log(Survival)) vs. Log (Years to Impairment) by Age Category



Results of the Cox proportional hazards model that adjusted for noise exposure during the period of the study revealed that for each additional year of age, the hazard ratio for experiencing hearing impairment was 1.092 (95% CI = 1.081 to 1.103, χ^2 = 279.02, $p < 0.001$). Thus, older workers had a higher probability of experiencing noise impairment at all time periods as compared to younger workers. Figure 10 contains a graphical depiction of these results.

Figure 10

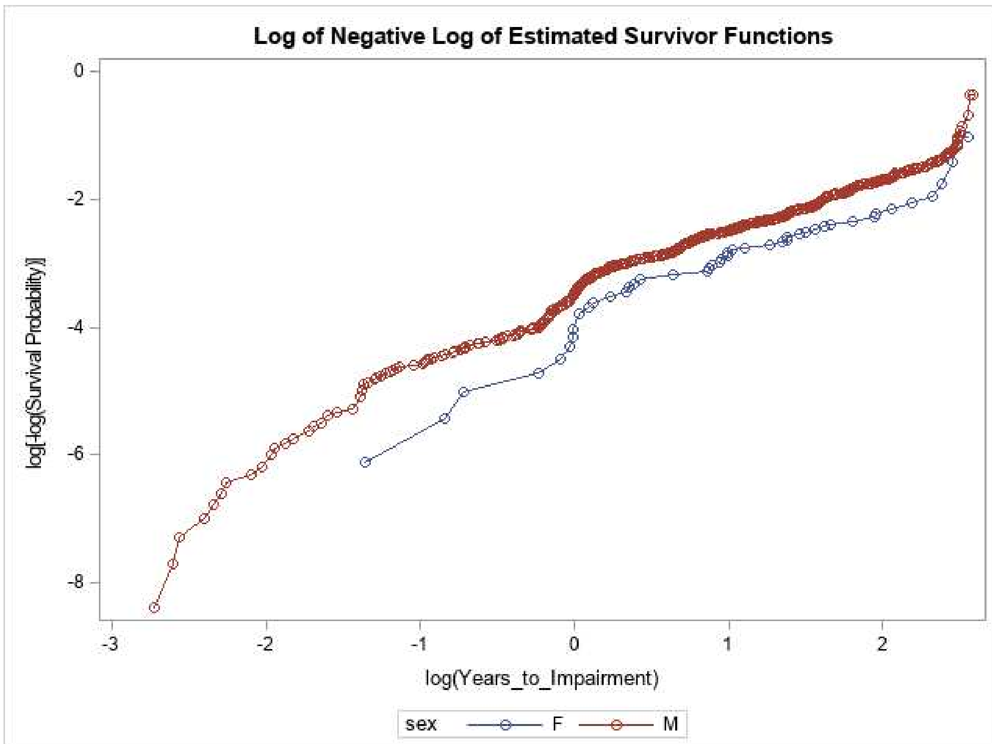
Survival Curve for Hearing Impairment by Age Category, Adjusted for Noise Exposure



Directional hypothesis 1b predicted that male workers would be at greater risk of experiencing hearing impairment than female workers as measured by annual audiometry testing. Initially, to determine if the assumption of proportional hazards was met, a plot of log(-log(survival)) vs. log (years to impairment) was created (Figure 11). As can be observed from the figure, the slopes for males and females are relatively parallel, thus there is no evidence to dismiss the assumption of proportional hazards.

Figure 11

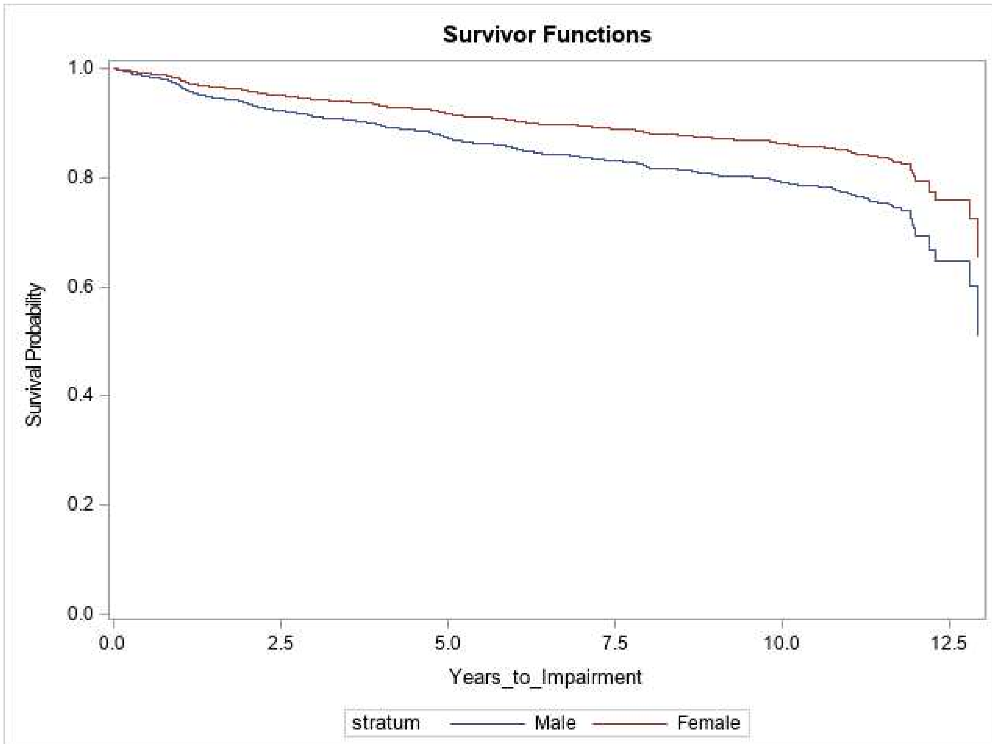
Log(-Log(Survival)) vs. Log (Years to Impairment) by Sex



Results of the Cox proportional hazards model that adjusted for noise exposure during the period of the study revealed that being female was protective as the hazard ratio for experiencing hearing impairment was 0.634 (95% CI = 0.470 to 0.855, $\chi^2 = 8.90$, p = 0.003). Thus, male workers had a higher probability of experiencing hearing impairment at all time periods as compared to female workers. Figure 12 contains a graphical depiction of these results.

Figure 12

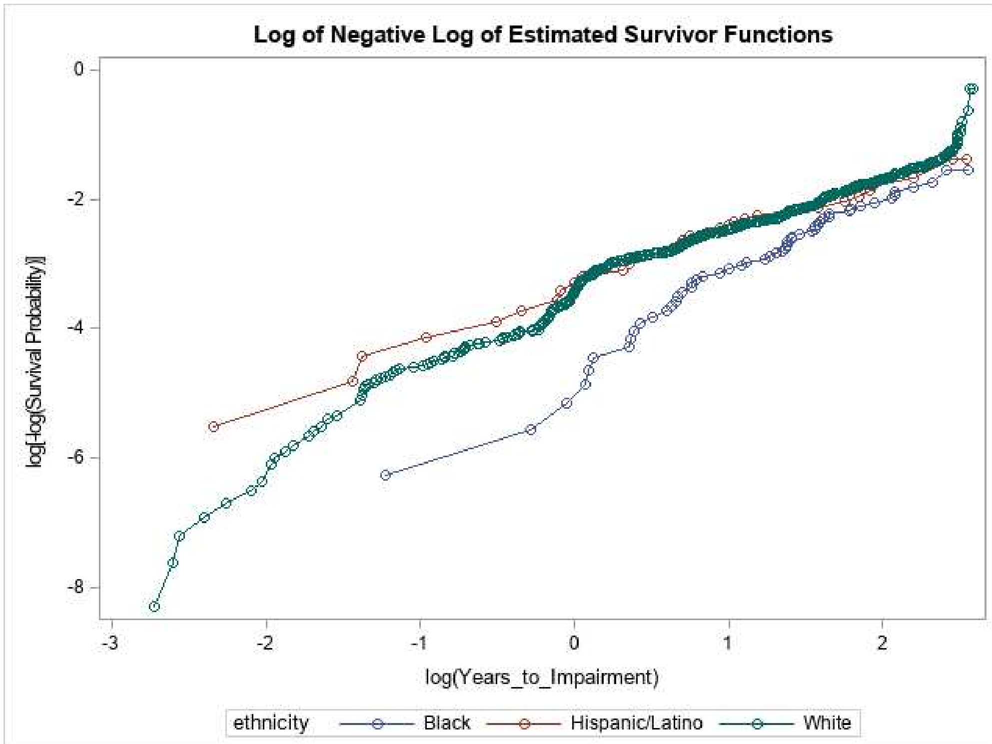
Survival Curve for Hearing Impairment by Sex, Adjusted for Noise Exposure



Directional hypothesis 1c predicted that African American workers would be at decreased risk of experiencing hearing impairment than workers of other races as measured by annual audiometry testing. Initially, to determine if the assumption of proportional hazards was met, a plot of log(-log(survival)) vs. log (years to impairment) was created (Figure 13). As can be observed from the figure, the slopes of the various race categories are relatively parallel, thus there is no evidence to dismiss the assumption of proportional hazards.

Figure 13

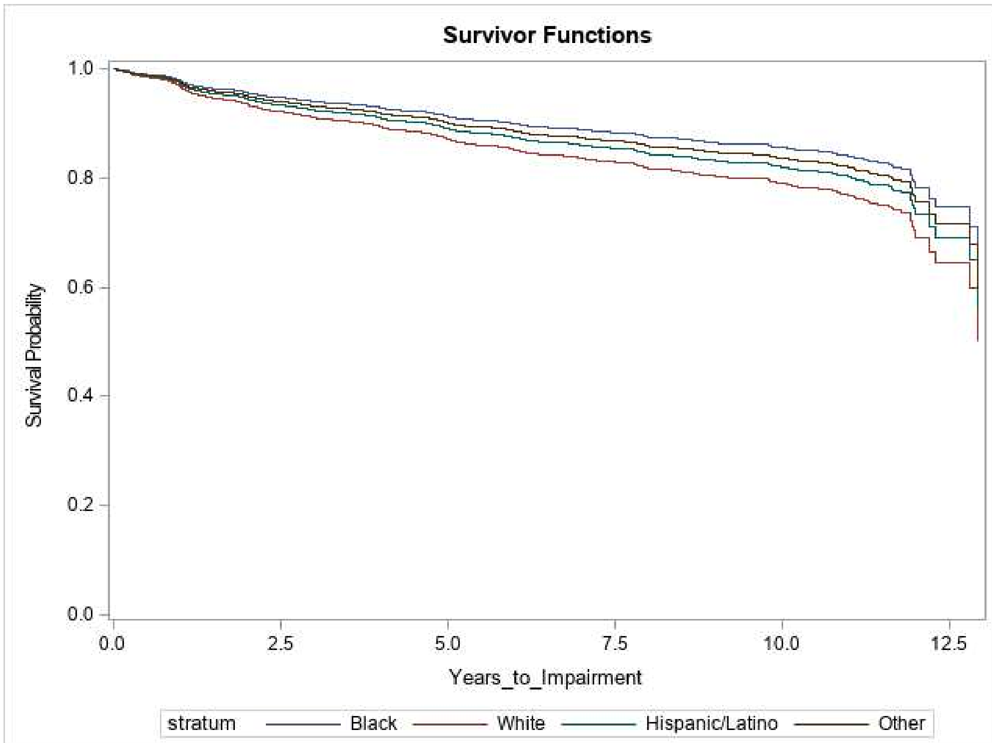
Log(-Log(Survival)) vs. Log (Years to Impairment) by Race



Results of the Cox proportional hazards model that adjusted for noise exposure during the period of the study revealed that race was a significant predictor (χ^2=8.942, df=3, p=0.030). Compared to African American workers, the hazard ratio for experiencing hearing impairment for White workers was 1.511 (95% CI = 1.136 to 2.009, χ^2 = 8.069, p = 0.005). Hispanic/Latino workers also had an increased risk for experiencing hearing impairment than African American workers with a hazard ratio of 1.270 but this increased risk was not statistically significant (95% CI = 0.815 to 1.981, χ^2 = 1.113, p = 0.291). Thus, African American workers had the lowest probability of experiencing noise impairment at all time periods. Figure 14 contains a graphical depiction of these results.

Figure 14

Survival Curve for Hearing Impairment by Race, Adjusted for Noise Exposure



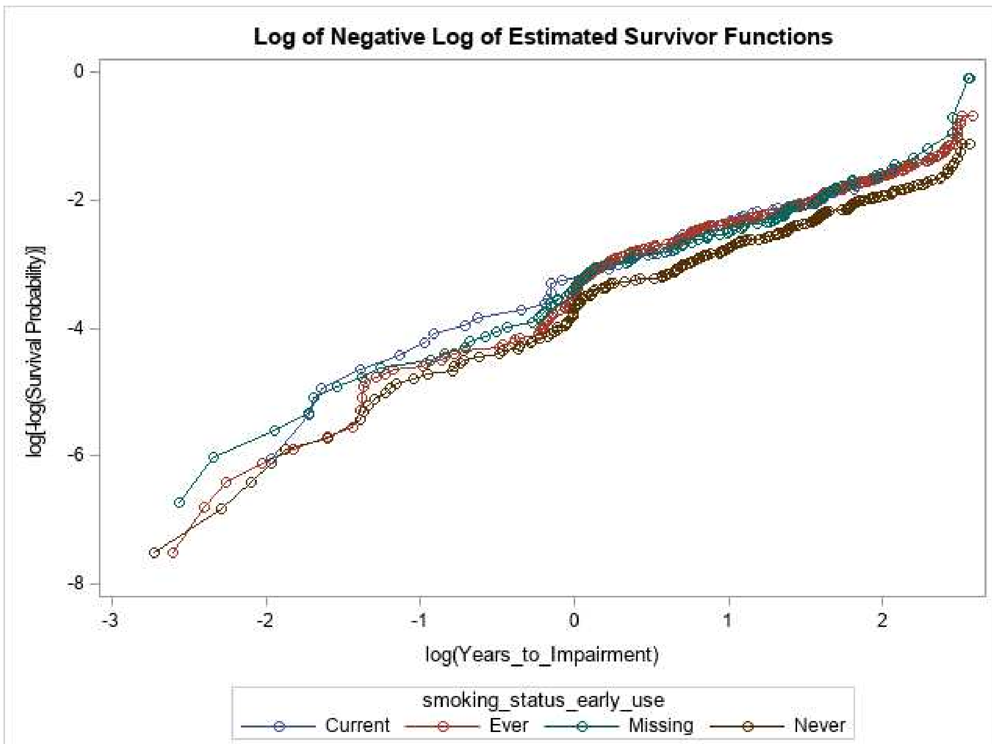
Research Question 2

The second research question was developed to determine the risk of developing hearing impairment for workers enrolled in the corporation's hearing conservation program by tobacco use as measured by annual audiometry testing. Directional hypothesis 2 predicted that workers that currently smoked would be at greater risk of developing hearing impairment than those workers that never smoked as measured by annual audiometry testing.

Initially, to determine if the assumption of proportional hazards was met, a plot of log(-log(survival)) vs. log (years to impairment) was created (Figure 15). As can be observed from the figure, the slopes of the various age categories are relatively parallel, thus there is no evidence to dismiss the assumption of proportional hazards.

Figure 15

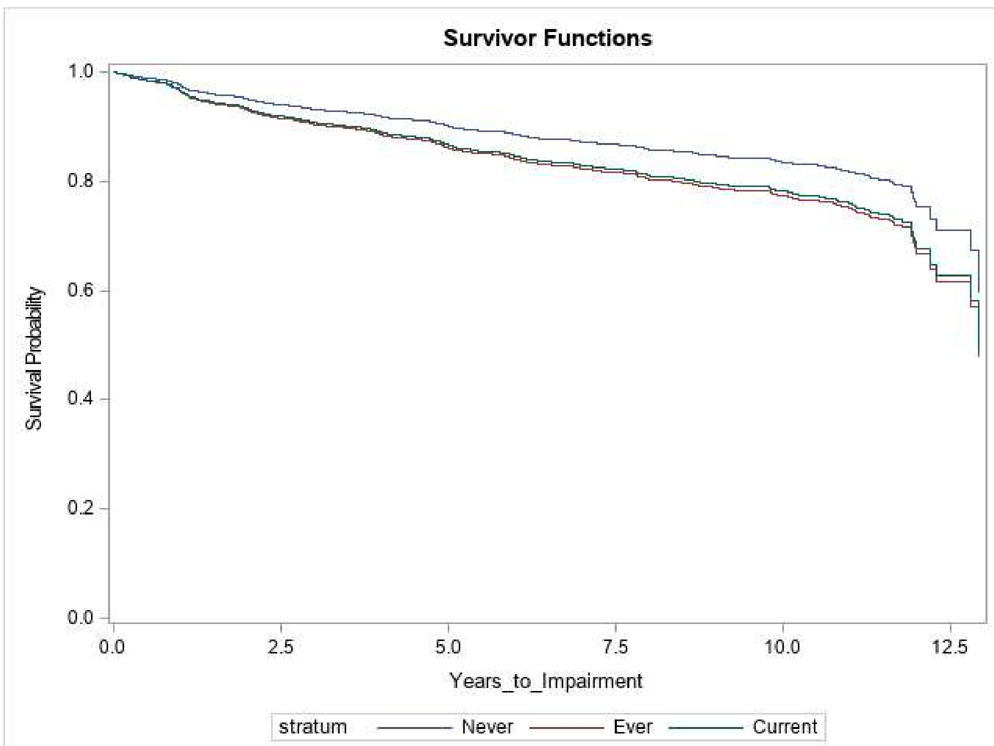
Log(-Log(Survival)) vs. Log (Years to Impairment) by Smoking Status



Results of the Cox proportional hazards model that adjusted for noise exposure during the period of the study revealed that smoking status was a significant predictor of hearing impairment (χ^2=18.893, df=3, p < 0.001). Compared to those workers that never smoked, the hazard ratio for experiencing hearing impairment for workers that currently smoke was 1.373 (95% CI = 1.034 to 1.823, χ^2 = 4.797, p = 0.029). Previous smokers, designated as “Ever” also had an increased risk for experiencing hearing impairment over workers that never smoked with a hazard ratio of 1.427 (95% CI = 1.202 to 1.694, χ^2 = 16.539, $p < 0.001$). Thus, workers who never smoked tobacco had the lowest probability of experiencing noise impairment at all time periods. Figure 16 contains a graphical depiction of these results.

Figure 16

Survival Curve for Hearing Impairment by Smoking Status Adjusted for Noise Exposure



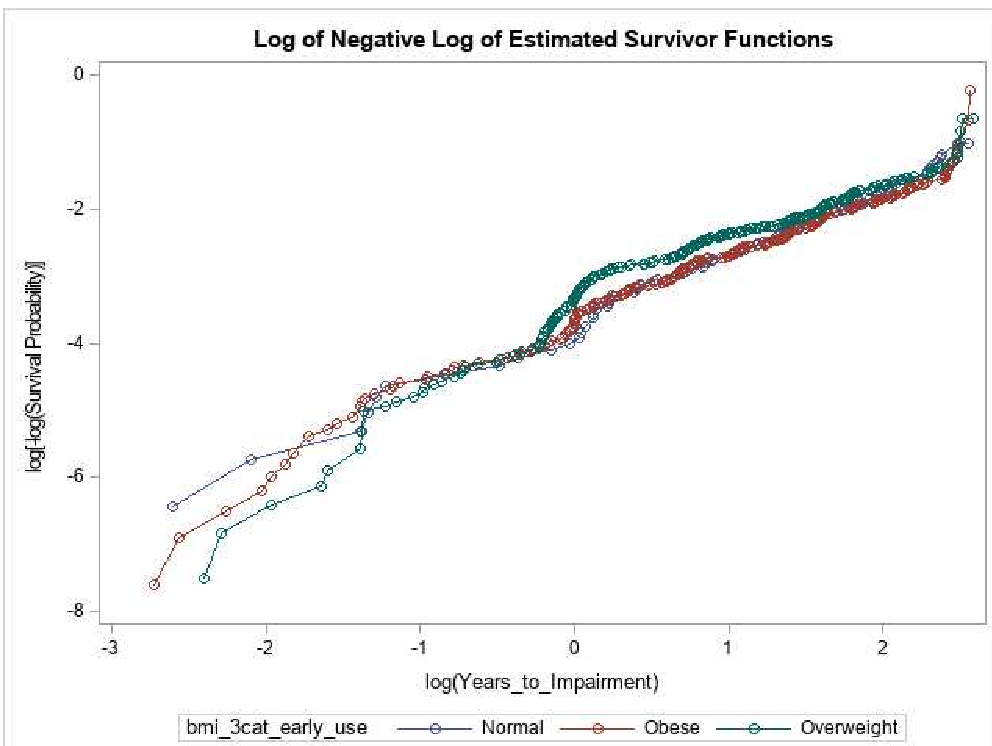
Research Question 3

The third research question was developed to determine the risk of developing hearing impairment for workers enrolled in the corporation’s hearing conservation program by health conditions as measured by annual audiometry testing. Directional hypothesis 3a predicted that obese workers would be at greater risk of developing hearing impairment than overweight workers and that overweight workers would be at greater risk of developing hearing impairment than normal weight workers as measured by annual audiometry testing.

Initially, to determine if the assumption of proportional hazards was met, a plot of log(-log(survival)) vs. log (years to impairment) was created (Figure 17). As can be observed from the figure, the slopes of the various BMI categories are relatively parallel, thus there is no evidence to dismiss the assumption of proportional hazards.

Figure 17

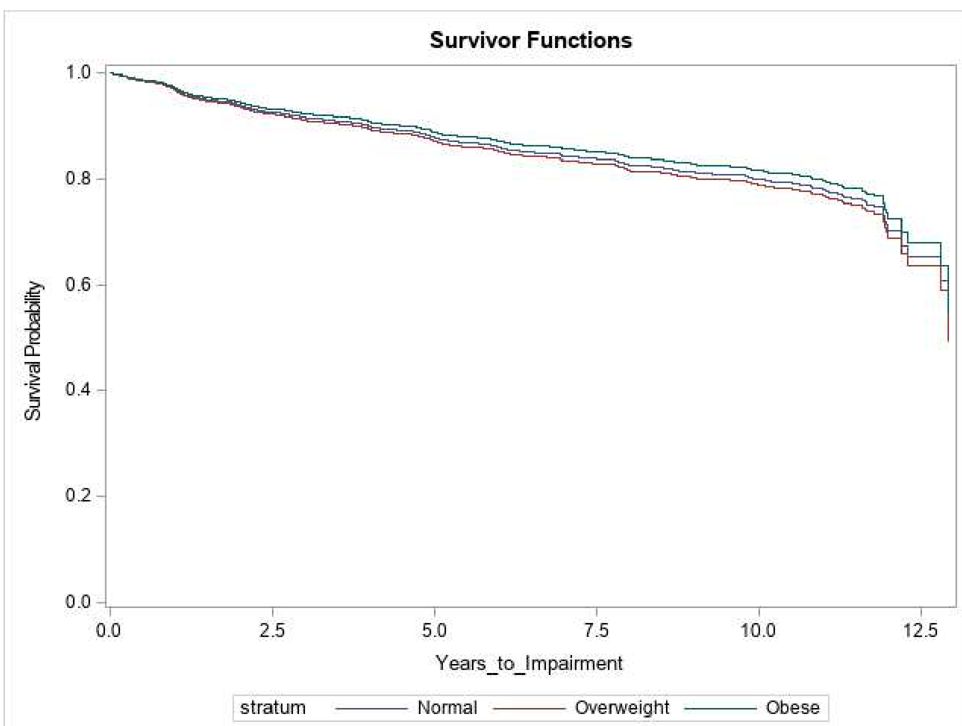
Log(-Log(Survival)) vs. Log (Years to Impairment) by Body Mass Index Category



Results of the Cox proportional hazards model that adjusted for noise exposure during the period of the study revealed that BMI category was not a statistically significant predictor of hearing impairment (χ^2=3.247, df=2, p = 0.197). Compared to workers with normal BMI, the hazard ratio for experiencing hearing impairment for overweight workers was 1.058 (95% CI = 0.835 to 1.342, χ^2 = 0.220, p = 0.639). Note that this was not statistically significant. Obese workers had an estimated decreased risk for experiencing hearing impairment compared to normal BMI workers with a hazard ratio of 0.910 (95% CI = 0.716 to 1.156, χ^2 = 0.603, p = 0.438). Again, this was not statistically significant. Thus, BMI category was not a significant predictor of hearing impairment. Figure 18 contains a graphical depiction of these results.

Figure 18

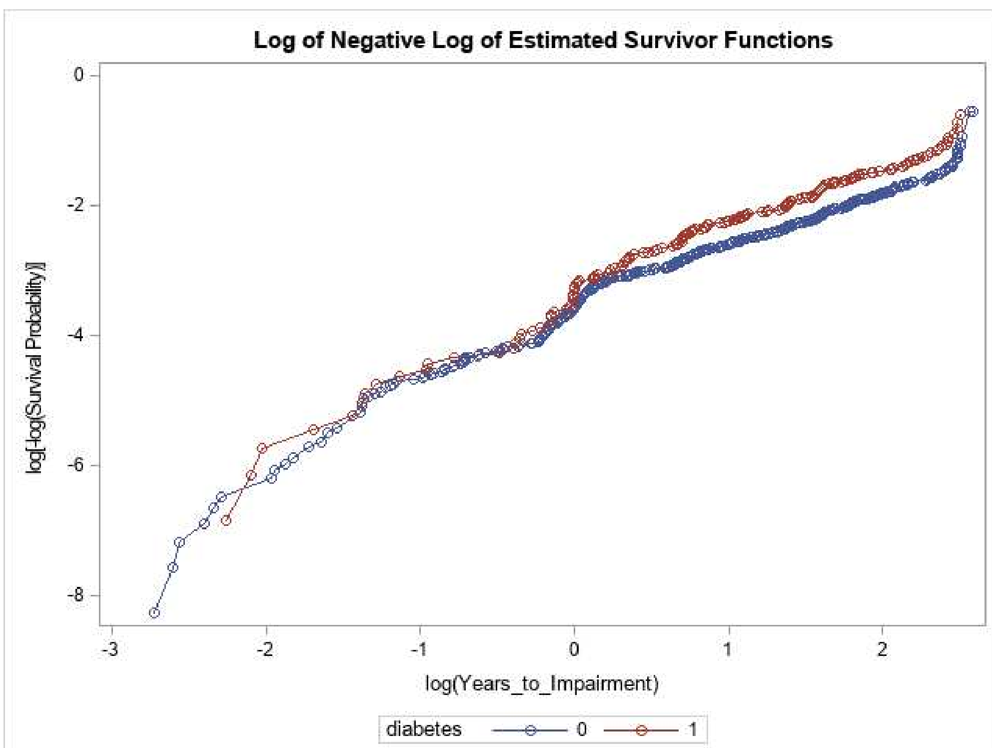
Survival Curve for Hearing Impairment by BMI Category, Adjusted for Noise Exposure



Directional hypothesis 3b predicted that diabetic workers would be at greater risk of developing hearing impairment than workers without diabetes as measured by annual audiometry testing. Initially, to determine if the assumption of proportional hazards was met, a plot of log(-log(survival)) vs. log (years to impairment) was created (Figure 19). As can be observed from the figure, the slopes for those workers with and without diabetes are relatively parallel, thus there is no evidence to dismiss the assumption of proportional hazards.

Figure 19

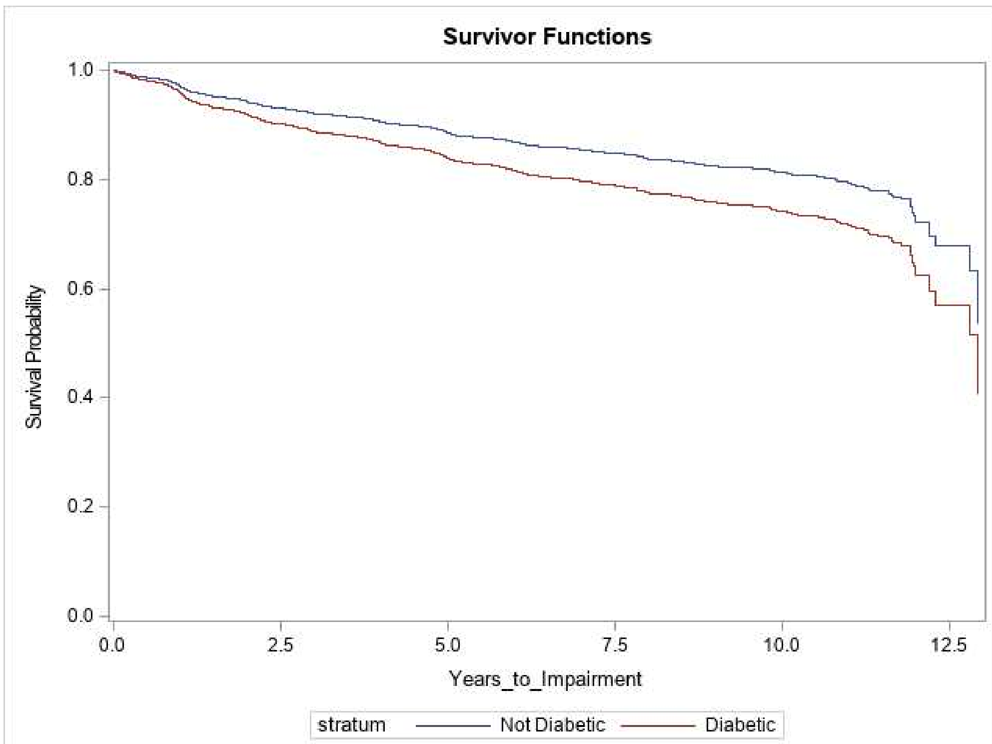
Log(-Log(Survival)) vs. Log (Years to Impairment) by Diabetes Status



Results of the Cox proportional hazards model that adjusted for noise exposure during the period of the study revealed that being diabetic was a risk for hearing loss as the hazard ratio for experiencing hearing impairment was 1.439 (95% CI = 1.215 to 1.706, $\chi^2 = 17.714$, $p < 0.001$). Diabetic workers had a higher probability of experiencing hearing impairment at all time periods as compared to workers without diabetes. Figure 20 contains a graphical depiction of these results.

Figure 20

Survival Curve for Hearing Impairment by Diabetes Status, Adjusted for Noise Exposure



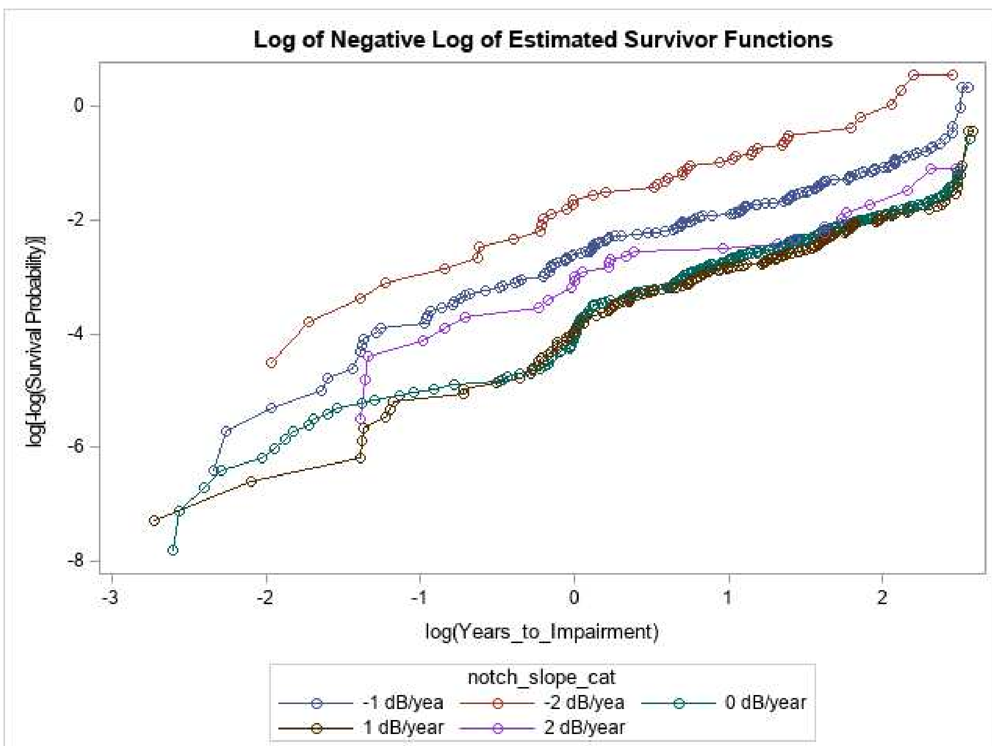
Research Question 4

The fourth research question was developed to determine the risk of experiencing noise induced hearing loss for workers enrolled in the corporation's hearing conservation program by level of hearing loss, as measured by their change in noise notch (notch slope), during their early work history. Directional hypothesis 4 predicted that workers that experienced greater hearing loss early in their work history would be at greater risk of developing hearing impairment than workers that experienced lesser hearing loss early in their work history as measured by annual audiometry testing.

Initially, to determine if the assumption of proportional hazards was met, a plot of log(-log(survival)) vs. log (years to impairment) was created (Figure 21). As can be observed from the figure, the slopes of the various notch slope categories are relatively parallel, thus there is no evidence to dismiss the assumption of proportional hazards.

Figure 21

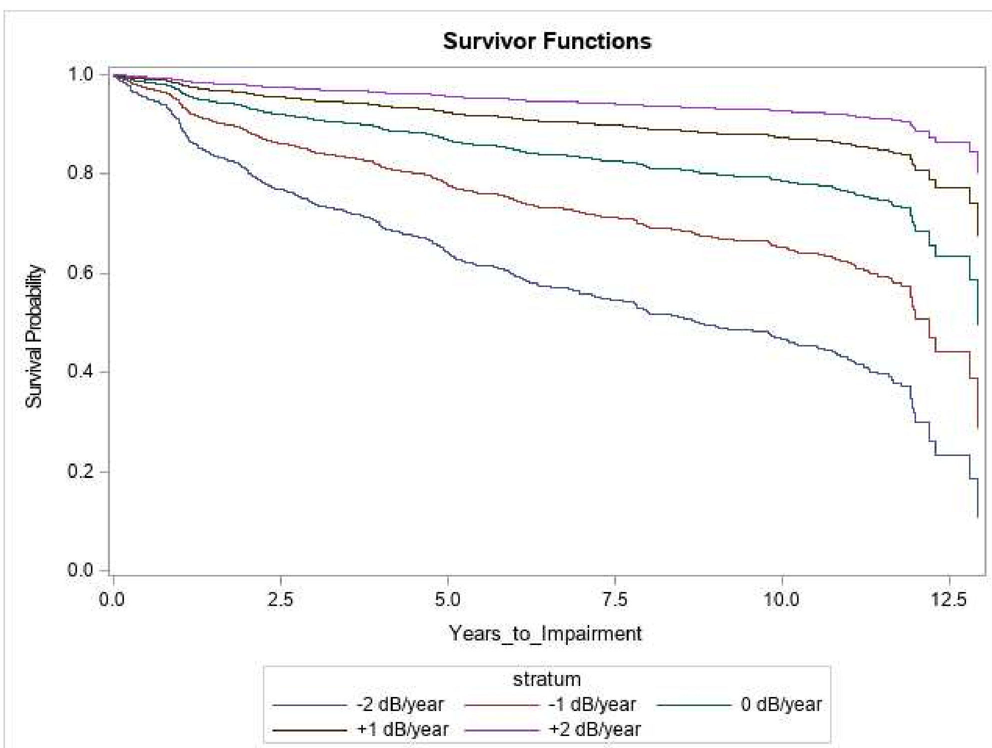
Log(-Log(Survival)) vs. Log (Years to Impairment) by Notch Slope Category



Results of the Cox proportional hazards model that adjusted for noise exposure during the period of the study revealed that for each additional change in notch decibel per year during a worker's early work history, the hazard ratio for experiencing hearing impairment was 0.562 (95% CI = 0.509 to 0.621, χ^2 = 129.29, p < 0.001). Thus, the greater the increase in noise notch during a worker's early work history, the lower the probability of experiencing hearing impairment at all later time periods. This result is in direct contrast to the expected findings. Figure 22 contains a graphical depiction of these results.

Figure 22

Survival Curve for Hearing Impairment by Noise Notch Category, Adjusted for Noise Exposure



Research Question 5

The final research question was developed to determine which demographic, lifestyle, and occupational factors are associated with the risk of experiencing noise induced hearing loss for workers enrolled in a corporation's hearing conservation program as measured by annual audiometry testing. The results of the parsimonious proportional hazards model that was developed through the use of a backward elimination strategy with a significance level of p = 0.05 is shown in Table 3.

Table 3

Results of Proportional Hazards Parsimonious Model

Parameter	Level	Parameter estimate	Standard error	χ^2	Hazard ratio Point estimate	Hazard ratio L95%	Hazard ratio U95%	Wald χ^2
Age	Per year	0.087	0.005	259.690***	1.091	1.079	1.102	259.690***
Sex	Female	-0.758	0.206	13.571***	-	-	-	13.571***
	Male	0 (reference)	-	-	-	-	-	
Race	White	0.535	0.147	13.185***	1.7708	1.279	2.280	16.048***
	Hispanic	0.173	0.226	0.582	1.188	0.763	1.851	
	Other	0.207	0.404	0.263	1.230	0.557	2.717	
	Black	0 (reference)	-	-	1 (reference)	-	-	
Smoking status	Current	0.241	0.146	2.748	1.272	0.957	1.691	10.931*
	Previous	0.170	0.088	3.755	1.186	0.988	1.409	
	Unknown	0.376	0.119**	10.025	1.457	1.154	1.839	
	Never	0 (reference)	-	-	1 (reference)	-	-	
Leq	Per dB	0.027	0.009	8.065**	1.027	1.008	1.045	8.065**
Notch slope	Per dB/year	-0.541	0.050	117.182***	-	-	-	117.182***
Notch slope*Sex	Female	0.872	0.224	15.212***	-	-	-	15.212***
	Male	0 (reference)	-	-	-	-	-	

Note. Hazard ratio not computable for parameters included in interaction

$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

As can be seen, there are six predictors that were found to have a statistically significant association with developing hearing impairment. Four of these predictors (age, race, smoking status and equivalent continuous sound pressure level (L_{eq})) only had main effects whereas there was an interaction between sex and change in notch level per year during a worker's first five years of audiometric testing at the workplace. The parsimonious model is defined as:

$$h(t) = h_0(t)\ \mathbf{exp}\ (\beta_{age}*\text{Age} + \beta_{sex}*\text{Sex} + \beta_{race}*\text{Race} + \beta_{smokingstatus}*\text{SmokingStatus} + \beta_{Leq}*\text{Leq} + \beta_{notchslope}*\text{NotchSlope} + \beta_{sex\_notchslope}*\text{Sex}*\text{NotchSlope})$$

Results of the multivariate parsimonious Cox proportional hazards model revealed that for each additional year of age, the hazard ratio for experiencing hearing impairment was 1.091 (95% CI = 1.079 to 1.102, $\chi^2 = 259.69$, $p < 0.001$). Thus, older workers had a higher probability of experiencing noise impairment at all time periods as compared to younger workers. Figure 23 contains a graphical depiction of this result. The model results also found that race was a significant predictor (χ^2=16.048, df=3, p = 0.001). Compared to African American workers, the hazard ratio for experiencing hearing impairment for White workers was 1.708 (95% CI = 1.279 to 2.280, $\chi^2 = 13.185$, $p < 0.001$). Hispanic/Latino workers also had an increased point estimate of risk for experiencing hearing impairment compared to African American workers with a hazard ratio of 1.188 but this increased risk was not statistically significant (95% CI = 0.763 to 1.851, $\chi^2 = 0.582$, p = 0.446). Other races also had an increased point estimate of risk for experiencing hearing impairment compared to African American workers with a hazard ratio of 1.230 but this increased risk was also not statistically significant (95% CI = 0.557

to 2.717, $\chi^2 = 0.263$, $p = 0.608$). Thus, White workers had the highest probability of experiencing noise impairment at all time periods. Figure 24 depicts these results graphically.

Figure 23

Survival Curve for Hearing Impairment by Age Category, Adjusted for all Other Independent Predictors in the Parsimonious Model

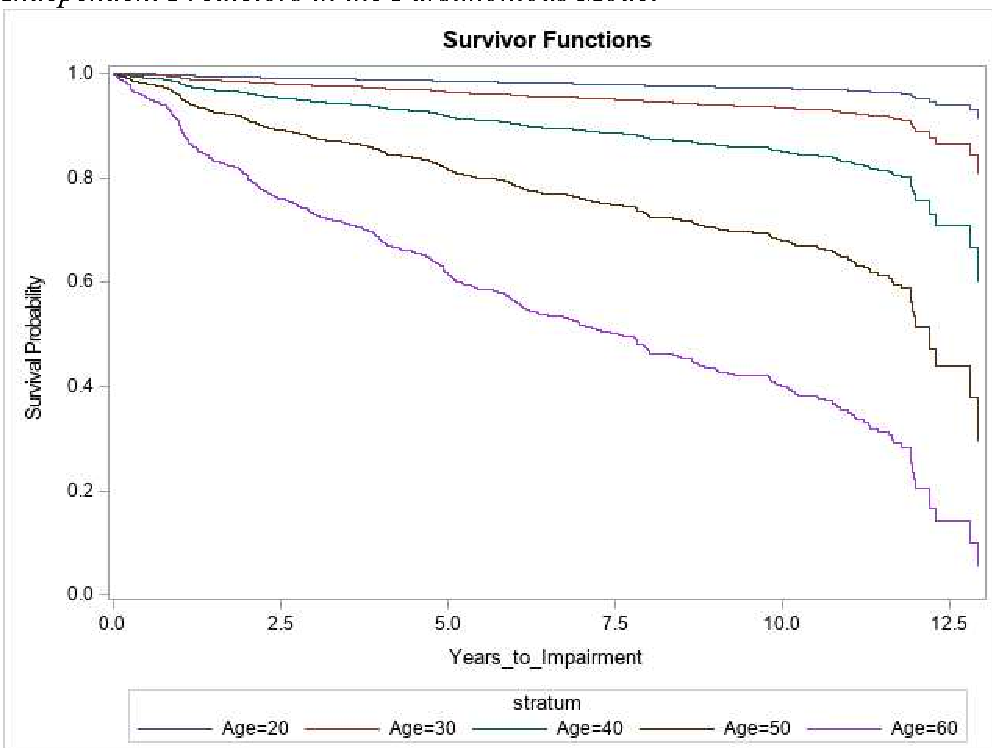
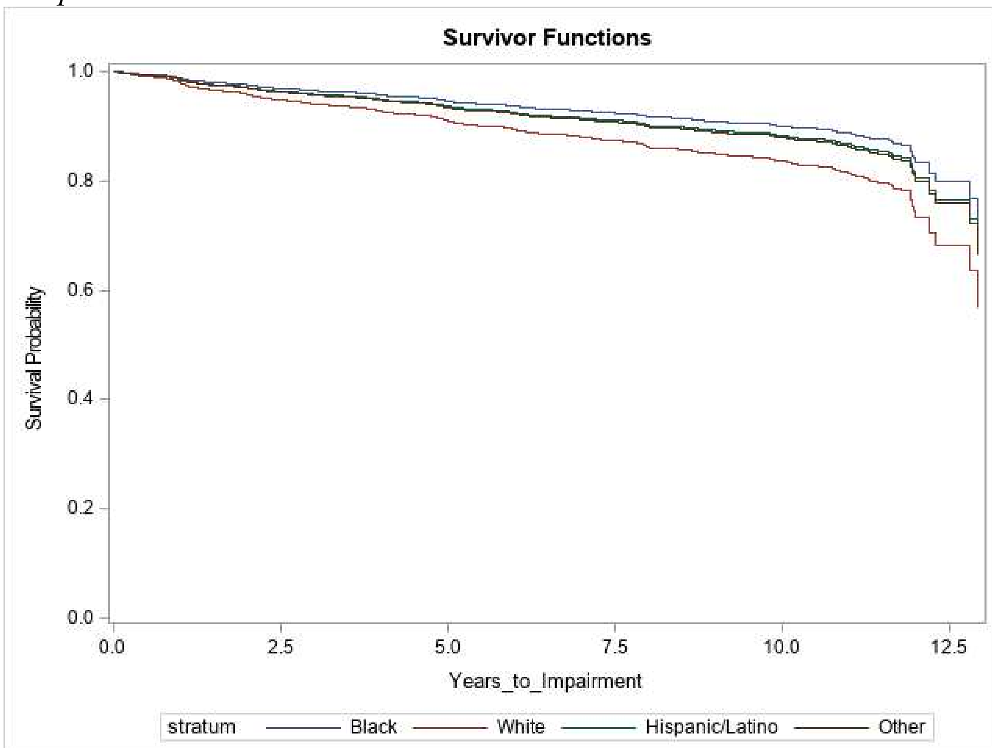


Figure 24

Survival Curve for Hearing Impairment by Race Category, Adjusted for all Other Independent Predictors in the Parsimonious Model

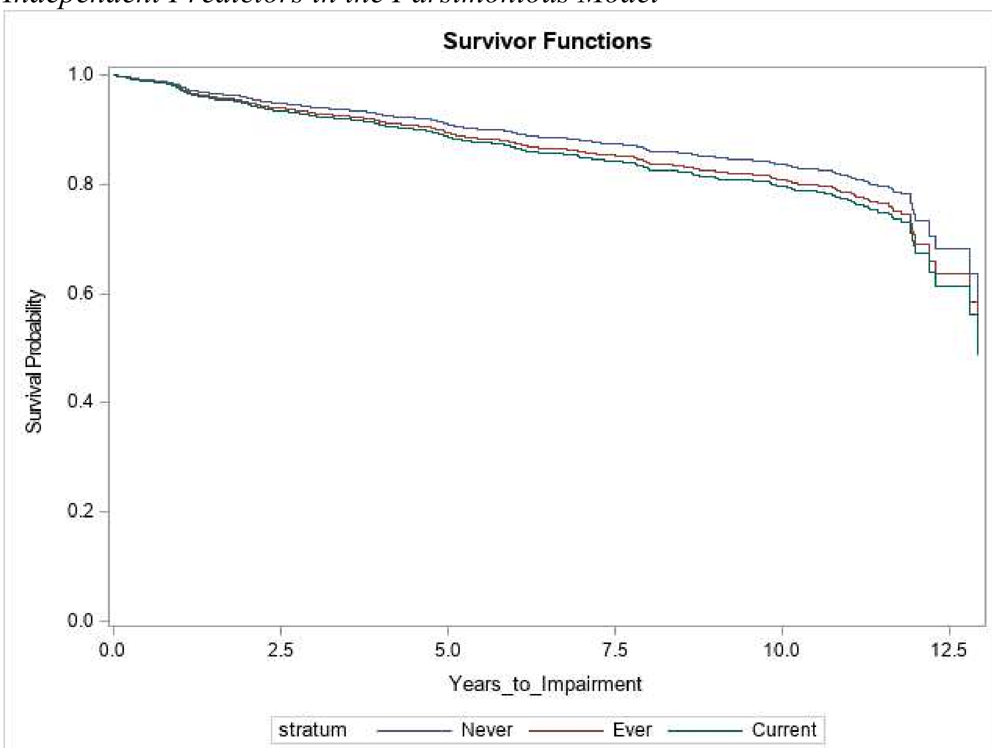


Smoking status was found to be a significant predictor of hearing impairment ($\chi^2 = 10.931$, df = 3, p = 0.012) in the multivariate parsimonious Cox proportional hazards model, though this was driven by the group of workers for which there was no information regarding their smoking status. Compared to those workers that never smoked, the point estimate of the hazard ratio for experiencing hearing impairment for workers that currently smoke was 1.272 but this was not statistically significant (95% CI = 0.957 to 1.691, $\chi^2 = 2.748$, p = 0.097). Previous smokers, designated as "Ever" also had an increased point estimate of risk for experiencing hearing impairment over workers that never smoked with a hazard ratio of 1.186 but, again, this was not statistically significant

(95% CI = 0.998 to 1.409, $\chi^2 = 3.755$, p = 0.053). The category of workers for which there was no information regarding their smoking status had an increased risk of hearing impairment compared to those that never smoked with a hazard ratio for developing hearing impairment of 1.457 (95% CI = 1.154 to 1.839, $\chi^2 = 10.025$, p = 0.002). Figure 25 contains a graphical depiction of these results

Figure 25

Survival Curve for Hearing Impairment by Smoking Status, Adjusted for all Other Independent Predictors in the Parsimonious Model

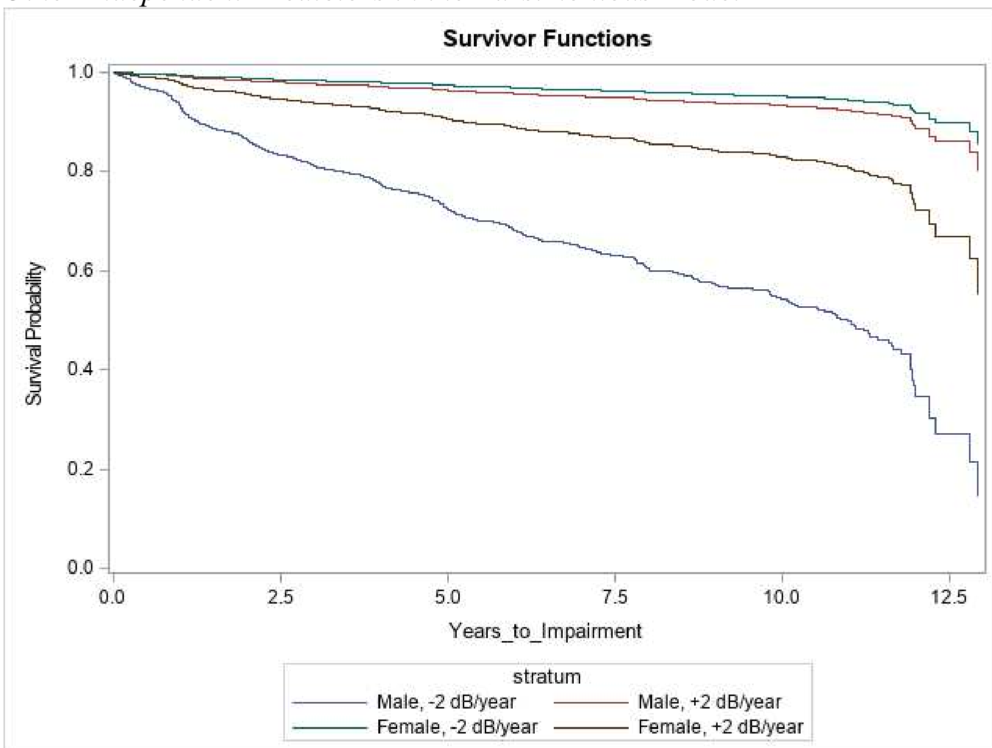


The effect of job noise level as determined by the equivalent continuous sound pressure level (L_{eq}) during the study was found to be significantly associated with experiencing hearing impairment based upon the results of the multivariate parsimonious Cox proportional hazards model. Each additional decibel was associated with a hazard ratio of 1.027 (95% CI = 1.008 to 1.046, $\chi^2 = 8.065$, p = 0.005) for experiencing hearing impairment. Subjects in louder work environments had a higher probability of experiencing noise impairment at all time periods as compared to those in less noisy work environments.

The multivariate parsimonious Cox proportional hazards model also included the interaction between sex and slope of the noise notch during a worker's early work history. Examination of the results depicted graphically in Figure 26 reveal that for female workers, an increasing noise notch during their first five years of audiometric testing is associated with a higher likelihood of experiencing hearing impairment later in their work life. Only about 5% of female workers that had a -2 dB/year change in noise notch (i.e., a reduction in the noise notch over their first five years of audiometric testing at work) would be expected to experience hearing impairment after 10 years while approximately 17% of female workers that had a +2 dB/year change in noise notch would be expected to experience hearing impairment over this same time period. On the other hand, roughly 44% of male workers that had a -2 dB/year change in noise notch would be expected to experience hearing impairment after 10 years while approximately 6% of male workers that had a +2 dB/year change in noise notch would be expect to experience hearing impairment over this same time period. The effect of an increasing noise notch during the first five years of audiometric testing yields a higher likelihood for hearing impairment for female workers while it suggests a decreased risk of hearing impairment for male workers.

Figure 26

Survival Curve for Hearing Impairment by Sex and Noise Notch Slope, Adjusted for all Other Independent Predictors in the Parsimonious Model



Summary

A total of 49,236 completed audiograms obtained from 4,894 workers enrolled in the corporation's hearing protection program for the purpose of annual examination were used for this study. On average, each subject contributed 10 audiograms. Among the 4,894 workers that were in the study, 708 developed hearing impairment per the American Medical Association definition. The first five years of audiograms were used to determine the average change in noise notch per year for each worker. Workers were then followed for up to 13.24 additional years to determine time to hearing impairment. The average time of follow-up was 5.69 years.

Six parameters were found to be predictors of hearing impairment, namely, age, sex, race, smoking status, average noise level at the job site, and the average change in noise notch per year during a worker's first five years of being in the company's hearing conservation program. Two of these factors, sex and the average change in noise notch per year, had a significant interaction with regard to their association with development of hearing impairment. Overall, older, White workers that currently smoked tobacco and were exposed to noisier job sites had the greatest risk of developing hearing impairment.

The average change in noise notch per year during a worker's first five years in the company's hearing conservation program had different effects on the risk of developing hearing impairment depending upon the worker's sex. For female workers, an increasing noise notch during their first five years of audiometric testing was associated with a higher likelihood of experiencing hearing impairment later in their work life. For male workers, however, the effect of an increasing noise notch was associated with a lower likelihood of experiencing hearing impairment later in their work life.

In the next section, Chapter 5, a summary of the study findings will be presented and conclusions offered based upon the statistical analysis of the study data. The chapter will conclude with a discussion of the positive social change implications of the study findings, the limitations of the study, as well as recommendations regarding the future direction and research of predictors of noise induced hearing loss.

Chapter 5: Discussion

The field of occupational medicine focuses its attention upon the prevention of disease as well as the promotion of worker wellness (Roberts, 1978). Although hearing conservation programs have been in place for over 30 years within the United States, NIHL remains the highest prevalence of all occupational diseases in the manufacturing sector and accounts for over 10% of recordable illnesses (Hamill, 2017; NIOSH, 2014). There is growing evidence of a genetic influence on susceptibility to NIHL which may help to explain the large variability in observed hearing loss to those exposed to similar levels of noise. Currently, the ability to predict those people with an increased propensity for NIHL is quite limited (Bovo et al., 2007; Themann et al., 2015). The purpose of this study was to provide a quantitative analysis of measured hearing loss among employees enrolled in a corporation's hearing conservation program. The goal of this study was to determine the underlying factors predisposing people to NIHL as well as the association between early occupational hearing loss and future risk of hearing impairment. This study's findings described the risk of hearing loss in terms of demographic, lifestyle, and occupational factors.

Summary and Interpretation of Findings

The results from a total of 49,236 occupational annual audiometric examinations of 4,894 individuals were analyzed for this study. The first 5 years of audiometric testing on these individuals were used to calculate their early work history hearing loss. The time to hearing impairment discussed in Chapter 4 did not include those 5 years. In this section, the 5 years will be added when discussing total time from being enrolled in the company's hearing conservation program until hearing impairment.

Age

Increasing age was associated with an increased hazard ratio for developing hearing impairment. Older workers had a higher probability of experiencing hearing impairment at all times compared to younger workers. Fifteen years after entering the corporation's hearing conservation program, a 20-year-old worker has a 2% chance of experiencing hearing impairment. This probability increases to 16% for a 40-year-old worker and to 63% for a 60-year-old worker. Although some of the increasing risk with age may be due to presbycusis, hearing impairment is defined by the results of pure tone hearing threshold levels obtained from 500, 1k, 2k, and 3k Hz. Presbycusis, on the other hand, tends to be observed in the higher frequencies of 4k, 6k, and 8k Hz. Thus, the increased risk of hearing impairment associated with increasing age appears to be the result of occupational exposure to noise.

Race

The results of this study are consistent with previously published findings in that African Americans have a lower risk of developing hearing impairment than Whites (Lin et al., 2012; Varghese & Kottaramveettil, 2019). The study results indicate that, at any point in time, for every 10 African Americans that experience hearing impairment, 17 White workers would develop hearing impairment. The hazard of developing hearing impairment for workers of all other races was between that of White workers and African American workers, but this hazard was not significantly different from either of these two groups. Fifteen years after entering the corporation's hearing conservation program, an African American worker has a 14% chance of experiencing hearing impairment, and this increased to 19% for a White worker. It is likely that genetic differences between the two races may account for the observed difference in the risk of developing hearing impairment.

Smoking Status

Findings from this study suggest that smoking status is a significant predictor of hearing impairment. However, this significant result was due to those for which there was no smoking status information in data supplied by the corporation. The group of workers for which smoking information was not available had a 50% higher hazard for developing hearing impairment than those that had noted that they never smoked. This finding is a bit problematic, as those that were missing smoking status information would be made up of workers that either never smoked, previously smoked, or were still current smokers. Thus, the hazard for those workers for which there was no information regarding their smoking status should have had a hazard within the range observed in the other three categories. This suggests some sort of bias in the missing smoking data. Removing those workers for which there was no smoking status information and rerunning the multivariate proportional hazards model revealed that smoking status was no longer statistically significant. This loss of statistical significance is not due to the reduction in sample size, as there were still 4,052 subjects included in the analysis and the loss of power associated with the loss of 842 subjects is negligible. I conclude that smoking status is likely not associated with the likelihood of experiencing hearing impairment.

Sex and Early Noise Notch Slope

Findings from this study indicate that worker sex and the annualized change in noise notch over the worker's first 5 years in the corporation's hearing conservation program interact with regard to their effect on the likelihood of experiencing hearing impairment. Fifteen years after entering the hearing conservation program, a male worker that experienced a -2 dB/year change in noise notch over his 5 five years would have a 45% chance of experiencing hearing impairment. A female worker with that same annualized change in noise notch over her first 5 years in the corporation's hearing conservation program would have a 6.5% chance of having hearing impairment. In contrast, 15 years after entering the corporation's hearing conservation program, a male worker that experienced a +2 dB/year change in noise notch over his first 5 years would have a 7.5% chance of experiencing hearing impairment. A female worker with that same annualized change in noise notch over her first 5 years in the corporation's hearing conservation program would have a 17% chance of having hearing impairment. Therefore, the effect of an increasing noise notch early in a worker's career is a significantly worse indicator of experiencing hearing impairment later in their career for female workers than it is for male workers. Additionally, experiencing a reduction in the noise notch early in a worker's career is a significantly worse indicator of experiencing hearing impairment later in their career for male workers than it is for female workers. The highest likelihood of experiencing hearing impairment later in a worker's career is a male worker that has a reduction in their noise notch over their first 5 years enrolled in a hearing conservation program. The reason for these observed differences between male and female workers is unclear. It is unlikely to be due to a regression toward the mean given the substantial number of subjects included in the study. Although women accounted for less than 10% of the study population, there were still 463 female workers included in the study.

Clinical Significance

This discussion has mostly focused upon statistical significance of the study results. However, it is equally important to discuss the clinical significance of the study findings as these are the practical results of the study. The findings of this study have practical application to individuals working in jobs that are subject to OSHA's requirement of enrollment in a hearing conservation program. To put this into perspective, there are approximately 30 million Americans exposed to noise levels that are considered hazardous (Doosti et al., 2014; Rabinowitz, 2000). Understanding the demographic and occupational risk factors for developing hearing impairment obtained from this study will allow companies to develop and incorporate policies to help protect their employees. These policies could be tailored, for instance, to increase the frequency of training sessions and/or audiometric testing for those employees deemed to be at increased risk of hearing impairment. This might include workers entering the hearing conservation program that are over 40 years old, male workers that had a reduction in their noise notch level over the first 5 years of their enrollment in the hearing conservation program, and women that had an increase in their noise notch level over the first 5 years of their enrollment in the hearing conservation program.

Theoretical and Conceptual Framework

Occupational NIHL can be thought of as the result of individual behavior and company/government policies. The ecological model of health behaviors (McLeroy, Bibeau, Steckler, & Glanz, 1988) provided the framework for this study. Ecologic models of health behavior incorporate social and psychological influences while environmental and policy aspects of behavior are emphasized (Sallis et al., 2015). In this study, occupational NIHL is considered the result of individual behavior and company/government policies.

The corporation, in compliance with OSHA requirements, determined the noise exposure for each job and created a hearing conservation program to protect their employees working in areas where the noise level exceeded 85 dB as an 8-hour TWA. Both government and company policies are in place. Individual behavior is the result of intrapersonal factors as well as interpersonal processes and primary groups (Sallis et al., 2015). These factors can influence the extent to which workers enrolled in the hearing conservation program participate in the program and their adherence to using proper hearing protection devices as suggested by the hearing conservation program.

As noted above, environmental aspects are emphasized in the ecological model of health behaviors. The decision of the company to use engineering controls to eliminate damaging noise levels could eliminate the potential for occupational NIHL. Barring this, administrative controls could be incorporated to limit the time that employees work in noisy environments. Lastly, the availability of proper hearing protection devices is another environmental factor. The use of hearing protection devices was not included in this study as data were not readily available regarding the use of these devices.

There was also a conceptual framework that underpinned this study, namely the theory that NIHL is not only the result of mechanical damage through severe stress on the hair cells of the cochlea, but is also metabolic in nature. Acoustic over-stimulation can result in a large release of glutamate, a neurotransmitter, at the synapse of the ear's inner hair cell, causing a quick increase in ROS and a release of free radicals in the cochlea. This process results in neuronal or hair cell death through the process of apoptosis (Kopke et al., 2015). Any behavioral, demographic, or occupational factor that is associated with propensity for NIHL may function through their effect on this metabolic process. These predisposing factors affect the relationship between noise exposure and rate of hearing loss.

Limitations

This study holds many strengths. It used an existing large cohort of longitudinal noise-exposed workers for which repeated audiometric records were available. The existing database allowed for individual workers to be followed over time to determine whether they experienced hearing impairment and if so, the timing of that determination. Availability of job-level noise sampling data enabled adjustment for noise exposure in statistical models and enhance the confidence of the findings. The ability to access demographic data on this cohort including sex, age, and race/ethnicity, and medical claims data including diagnosis of diabetes, allowed model adjustment for these factors as well.

Even with these strengths, there were limitations to the study. Information on hearing trajectories prior to enrollment in the company's hearing conservation program was unavailable. Because the mean age at a subject's first audiogram was 36 years, unobserved changes in hearing prior to their first audiogram could have had an impact on the results. The study was unable to use information regarding the use and effectiveness of hearing protection devices by subject.

The results from audiometric testing on the workers was presumed to be both accurate and reliable. In the United States, which is where the data used in this study originated, government regulations require audiometric testing to be conducted with calibrated audiometers that meet the American National Standard Institute specifications of SC-1969 (Leonard, 2009). It was assumed that the results of audiometric testing used in this study met that criteria and were accurate with regard to hearing threshold levels.

The study used a single metric (American Medical Association's hearing impairment) to define the outcome of hearing loss. This choice was based on two separate reasons. First, the audiometric frequencies used to calculate hearing impairment are important for speech communication. Second, most states that consider occupational hearing loss a compensable injury use this definition of hearing loss for the basis of a claim.

The study was conducted using secondary data. Certain subgroups had limited representation including current smokers, females, African Americans, and Hispanics. The inferences based on the results of the study should be viewed accordingly.

These limitations notwithstanding, the study results reveal an opportunity to identify workers at risk for hearing impairment early in their working career. Hearing loss prevention strategies could then target this population of employees with the intent of reducing hearing loss over their career.

Recommendations for Future Research

This study provided a longitudinal analysis of hearing loss among employees of a large multinational manufacturing corporation. It showed a predictive relationship between early occupational hearing loss, as measured by the annualized change in noise notch and the probability of experiencing hearing impairment later in an individual's work life. Future studies should be conducted to determine if similar findings are found in a different workforce as this would give greater credence to the results of this study.

The current study was unable to include information regarding the use and effectiveness of hearing protection devices used by the subjects of the study. Future studies should be undertaken that measure both the environmental noise level as well as the noise level at the subject's ear as the attenuation of the environmental noise exposure by the hearing protection device is likely to vary by subject. This potential variability may have introduced bias in the current analysis that could be evaluated in a future study.

All subjects in this study were assumed to have worked 8-hour shifts and that each subject worked the same number of days (shifts) throughout the study period. A future study that is able to include information on the actual hours a subject worked would allow for adjustments to be made in the calculation of each subject's equivalent continuous sound pressure level (Leq) potentially obtaining a more accurate measure of noise exposure. Additionally, non-occupational noise exposure was not considered in this study because this data was not available. A new study that includes reasonable estimates of non-occupational noise exposure by subject would be beneficial as it is possible that non-occupational noise exposure confounded some of the relationships evaluated within the current study.

Lastly, future studies should evaluate additional operationalized definitions of hearing loss. The current study only used the American Medical Association's definition of hearing impairment as its endpoint. Other operationalized definitions could use different combinations of pure tone frequencies as well as different threshold levels.

Positive Social Change

Walden University was founded as an entity for promoting positive social change and this goal remains its mission (Shepard, 2008). Research within the public health arena focuses on stimulating positive social change from individual-centric explanations (Stephan et. al., 2016). A relatively recent trend within public health is determining the ways in which complex behaviors that underlie positive social change may be modified through organizational practices. Community interventions in public health highlight how the resources and managerial practices of an organization can enable these changes (Hoddinott, Britten & Pill, 2010).

The ability to communicate effectively is fundamental to healthy aging. Hearing loss has been found to be independently associated with lower quality of life, social isolation, depression, accelerated cognitive decline, functional decline, increased hospitalization and health care use, and occurrence of dementia (Nieman & Oh, 2020). Therefore, any intervention that can reduce hearing loss on a population level can have a large positive social change because all of the aforementioned issues associated with hearing loss could be reduced. With regard to the association of dementia and prevalence of hearing loss, the prevention of hearing loss may be the largest modifiable risk factor for dementia within the population (Uchida et. al., 2019).

The findings from the current study will affect positive social change as they will inform policy decisions. The observed relationship between early career hearing loss, gender, and probability of experiencing hearing impairment will allow companies with hearing conservation programs to incorporate criteria that trigger additional education and, possibly, potential re-assignment of at-risk employees to jobs within their company with lower noise exposure. Again, this type of policy will reduce the societal burden of hearing loss.

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Appendix A: OHM (Audiometry)

Overview
This is the audiometry data for those employees included in the company's hearing conservation program. The data comes from the OHM (occupational health manager) software

Variable Descriptions:

Variable name	Brief description of variable
audio_serial_no	Serial number of audiometer
blol	OSHA STS baseline indicator – left ear
blor	OSHA STS baseline indicator – right ear
cal_date	Machine calibration date
dept_time_of_test	Code of the department the employee was working in at the time of the test
eessno	Unique employee number
examiner	Code or initials of person conducting the test (or name of vendor)
exposure	Period of exposure
job_time_of_test	Code of the job the employee was working in at the time of the test
l1k	Left ear hearing threshold at 1000 Hz
l2k	Left ear hearing threshold at 2000 Hz
l3k	Left ear hearing threshold at 3000 Hz
l4k	Left ear hearing threshold at 4000 Hz
l500k	Left ear hearing threshold at 500 Hz
l6k	Left ear hearing threshold at 6000 Hz
l8k	Left ear hearing threshold at 8000 Hz
lbl	Left ear revised baseline indicator
loc	Plant location
loc_time_of_test	Plant location of the test
noise_level	Ambient noise level
otologic_result_left	Left Ear Result
otologic_result_right	Right Ear Result
protection_type	Type of protection worn by employee
protection_type_desc	Description of protection type
r1k	Right ear hearing threshold at 1000 Hz
r2k	Right ear hearing threshold at 2000 Hz
r3k	Right ear hearing threshold at 3000 Hz
r4k	Right ear hearing threshold at 4000 Hz
r500k	Right ear hearing threshold at 500 Hz
r6k	Right ear hearing threshold at 6000 Hz
r8k	Right ear hearing threshold at 8000 Hz

rbl	Right ear revised baseline indicator
test_date	Test date
test_time	Time of test
test_type	Type of test: RO: Routine OB: Original Baseline RB: Revised Baseline RT: Retest IN: Invalid Test EX: Exit Audiogram LO: Layoff RW: Return to Work PP: Pre-Placement
trained_hpd	Trained in Hearing Protection Device

Appendix B: HyGenius

Overview:
Industrial hygiene sampling of jobs

Variable Descriptions:

Variable name	Brief description of variable
Agent_ID	Represents the sample analyte for which the results are provided.
Agent_Name	A description of the chemical or physical hazard of concern.
Analytical_Method	Identifies the analytical method that was used to analyze the sample for the agent.
Bldg_Area	Represents the building or area where the sample was collected. This is location specific.
Bldg_Area_ID	ID representing the building or area where the sample was collected. This is location specific.
Calibrated_By	Represents the person who calibrated the sampling equipment that was used to collect the sample.
Calibration_Date	The date that the equipment used to collect the sample was last calibrated.
Collection_Medium	A unique identifier for the filter, charcoal, or other material used to collect the analyte of concern from the air.
Comments	Free form text provided by the user to further describe the conditions surrounding sample collection.
Created_By	Unique user ID of the user who originally created the sample record in the system; may be the ID of the analytical laboratory originating the data, such as Clark Labs.
Created_By_Result	Same as Created_By field
Creation_Date_Result	Date the sample record was originally created in the system (not the sample date).
Date_Created_Sample	Appears to be the same as Creation_Date_Result
Date_Last_Modified_Result	Date that the sample result record was created or last modified by a person or process.

Date_Last_Modified_Sample	Unknown field
Department	Industrial hygiene department name: Industrial hygiene departments are defined by each location and represent IH-specific (logical) exposure-based work departments. This is part of the logical key that defines a unique SEG.
Department_ID	ID for the department
Elapsed_Time	The total number of minutes the equipment collected the sample. Both start time/stop time sets are used to calculate the elapsed_time.
Flow_Rate_LPM	Average of the pre_flow_rate and post_flow_rate, if those fields are provided. Otherwise, the user provided rate at which the pump was pulling air through the media.
Instrument	Free form text that may be used to further describe the instrument used to collect the sample.
Job	Industrial hygiene job title: Industrial hygiene jobs are defined by each location and represent IH-specific (logical) exposure-based job work. For example, workers with different pay grades would still be seen as having the same job. This is part of the logical key that defines a unique SEG.
Job_ID	ID for the job
Lab	Uniquely identifies the industrial hygiene analytical laboratory that analyzed the sample.
Lang_ID	Language ID of the plant
Language	Each physical location has a consistent language for the complete user interface. Current languages are: Brazilian Portuguese Canadian French Castilian Spanish Dutch English Icelandic
Last_Modified_By	Identifies last person to modify the record
Last_Modified_By_Result	Identifies the person or system to last modify the sample result
Loc_ID	Each physical location in the system has a unique ID. Part of the logical key that defines a unique SEG.
Location_Description	Description of the plant location

Non_Detect_Indicator	Symbol ("<") used to indicate that the reported result of the analyte was less than the detection level of the analytical equiment.
Operating_Conditions	Description of the ambient environment during the sampling period
Operating_Conditions_ID	ID used to describe the ambient environment during the sampling period. Unusual conditions are further described in the COMMENTS field. Current values include: 1 - Low 2 - Normal 3 - High
Percent_of_Limit	Calculated field describing the percent of the limit.
Post_Flow_Rate	The post-sampling rate at which the pump was pulling air through the media.
PPE_Body	Description of Body PPE
PPE_Body_ID	This field indicates the body PPE worn by the worker while the sample was collected. Values for this field are: 41 - Disposable Suit 42 - Chemical Suit 43 - Apron 44 - Jacket 45 - Other 46 - Not Used
PPE_Ear	Description of Ear PPE
PPE_Ear_ID	This field indicates the type of hearing PPE worn by the worker while the sample was collected. Values for this field are: 31 - Plugs 32 - Muffs 33 - Canal Caps 34 - Custom Molded 35 - Plugs & Muffs 36 - Other 37 - Not Used
PPE_Face	Description of Face PPE

PPE_Face_ID	This field indicates the facial PPE worn by the worker while the sample was collected. Values for this field are: 61 - Goggles 62 - Shield 63 - Welding Helmet 64 - Other 65 - Not Used
PPE_Hand	Description of Hand PPE
PPE_Hand_ID	This field indicates the type of hand PPE worn by the worker while the sample was collected. Values for this field are: 51 - Chemical Gloves 52 - Barrier Cream 53 - Other 54 - Not Used
PPE_Resp_Style	Description of PPE Respiratory Style
PPE_Resp_Style_ID	This field indicates the style of respiratory PPE worn by the worker while the sample was collected. Values for this field are: 21 - Full Face 22 - Half Face 23 - Quarter Face 24 - Helmet/Hood 25 - Other 26 - Not Used
PPE_Resp_Type	Description of PPE Respiratory Type
PPE_Resp_Type_ID	This field indicates the type of respiratory PPE worn by the worker while the sample was collected. Values for this field are: 11 - Mechanical Filter 12 - Chemical Cartridge 13 - SCBA 14 - Powered Air 15 - Supplied Air 16 - Other 17 - Not Used
Pre_Flow_Rate	The pre-sampling rate at which the pump was pulling air through the media.
Result	The raw result (not time weighted) of the analyte.

Sample_Cassette_Num	User assigned identifier of the collection medium that will be sent to a laboratory for analysis.
Sample_Date	Date that the sample was collected.
Sample_ID	Used to uniquely identify a sample when combined with the LOC_ID.
Sample_ID_Result	Field not used
Sample_Questionable	Field that indicates whether the results of the sample are believed to be questionable. Value is set to ‘Yes’ to indicate questionable status.
Sample_Status	Indicates whether the sample is valid (all fields complete) and able to be used in the baseline analysis statistical process. Current values are: Valid Suspended
Sample_Strategy	Current values include: 1 - Random 2 - Worst Case/Screening 3 – Diagnostic
Sample_Strategy_ID	Current values include: 1 - Random 2 - Worst Case/Screening 3 – Diagnostic
Sample_Type	A - Area Sample B - Bulk Sample O - Other P1 - Personal TWA Sample, No Exposure During Unsampled Time P2 - Personal TWA Sample, Equal Exposure During Unsampled Time P3 - Personal Peak Sample, Ceiling or STEL P4 - Personal Partial Shift TWA Merge Sample; No Exposure During P5 - Personal Sample -Other P6 - Personal Peak Sample - 5 Minute P7 - Personal Peak Sample - 10 Minute P8 - Personal Peak Sample - 15 Minute P9 - Personal Peak Sample - 30 Minute P10 - Personal Peak Sample - 60 Minute P11 - Personal Partial Shift TWA Merge Sample; Equal Exposure during unsampled time

	S - Source Sample W - Wipe Sample X - Blank
Sample_Type_ID	Sample time and/or calculation used. Current values are: A B O P1 P2 P3 P4 P5 P6 P7 P8 P9 P10 P11 S W X
Sampled_By	ID and name of person conducting the sample
Shift	Values for current shifts are the text descriptions: 1 - Day 2 - Evening 3 - Night
Shift_ID	A unique identifier that describes the shift worked while the sample was collected. Values for current shifts are the numbers: 1 - Day 2 - Evening 3 - Night
Shift_Length	A unique identifier that describes the shift length worked while this sample was collected. In HYGenius, current company shift lengths are 8, 10 and 12 hours. This is part of the logical key that defines a unique SEG.
Shift_Length_ID	A unique identifier that describes the shift length worked while this sample was collected. In HYGenius, current company shift lengths are 8, 10 and 12 hours. This is part of the logical key that defines a unique SEG.

Start_Time_1	The time the first sampling period began. There are two sets of start/stop times. Time is recorded using a 24-hr clock.
Start_Time_2	The time the second sampling period began. There are two sets of start/stop times. Time is recorded using a 24-hr clock.
Stop_Time_1	The time the first sampling period ended. There are two sets of start/stop times. Time is recorded using a 24-hr clock.
Stop_Time_2	The time the second sampling period ended. There are two sets of start/stop times. Time is recorded using a 24-hr clock.
Task	Task
Task_ID	ID of specific work task that was being performed during sampling. This is part of the logical key that defines a unique SEG.
TWA_Result	The Time Weighted Average (TWA) result; the result obtained from measuring exposure and averaging over the duration of the shift.
UOM	The Units of Measure for the analyte. Current values include: --- - No units DB - Decibels DBA - Decibels, A scale FCC - Fibers per Cubic Centimeter L - Liters LPM - Liters Per Minute MG - Milligram MGG - Milligram per gram of bulk material MGK - Milligrams per kilogram of bulk material MGL - Milligram per liter of bulk material MGM - Milligrams per Cubic Meter PPB - Parts Per Billion PPM - Parts Per Million SCC - Structures per cubic centimeter UG - Microgram UGC - Micrograms per 100 square centimeters UGG - Microgram per gram of bulk material UGL - Microgram per liter of bulk material UGM - Micrograms per Cubic Meter V% - Volume percentage WT% - Weight percentage

UOM_ID	The Units of Measure for the analyte. Current values include: --- - No units DB - Decibels DBA - Decibels, A scale FCC - Fibers per Cubic Centimeter L - Liters LPM - Liters Per Minute MG - Milligram MGG - Milligram per gram of bulk material MGK - Milligrams per kilogram of bulk material MGL - Milligram per liter of bulk material MGM - Milligrams per Cubic Meter PPB - Parts Per Billion PPM - Parts Per Million SCC - Structures per cubic centimeter UG - Microgram UGC - Micrograms per 100 square centimeters UGG - Microgram per gram of bulk material UGL - Microgram per liter of bulk material UGM - Micrograms per Cubic Meter V% - Volume percentage WT% - Weight percentage

Appendix C: PeopleSoft/PeopleView

Overview
This is the human resources file and contains data related to all employees.

Variable Descriptions:

Variable name	Brief description of variable
ACTION	Action: Reason for the database entry, 3-letter code used
ACTIONCD	Action code: Description of the Action
ACTIONDE	Action description: Same as above
ACTIONDT	Date that this change was made in the database
ACTIONRS	Action reason: More detail of the action, 3-letter code used. Code explained in REASONCD field
annual	Annual salary
BUNDESC	Business Unit Description: Over the years the BU names have changed.
BUSTITLE	Business Title: Field unknown
busunit	Business Unit: Field unknown
CLOCK_NB	Clock Number: Field unknown
cmpdendt	Field unknown
CMPSENDT	Field unknown
COMPABRV	Field unknown
COMPANY	Field Unknown
COMPDESC	Company Description: Provides information on provenance of the plant
COMPFREQ	Compensation Frequency: M=Monthly for Salaried Employees, H=Hourly for Hourly Employees
COMPRATE	Compensation Rate: Monthly salary or hourly rate
CONTSVDT	Field Unknown
COUNTRY	Country
CRAFTCD	Craft Code: Field Unknown
CRAFTDES	Craft Description: Field Unknown
CURRENCY	Country Currency
DEPTABR	Department Abbreviation: Internal alphanumeric code for the department
DEPTCODE	Department Code: Field Unknown
DEPTDT	Department Date: Field Unknown
DEPTID	Department ID: Typically the same as DEPTABR
DEPTNAME	Department Name: Detailed plant department title
deptscrt	Field Unknown
DEPTSNDT	Field Unknown
dobdt	Date of birth

ee4func	Equal Employment Function: Field Unknown
eejobgr	Equal Employment Job Grade: Field Unknown
EEO1CODE	Equal Employment Opportunity 1 Code: Field Unknown
eeo4code	Equal Employment Opportunity 5 Code: Field Unknown
eeo5code	Equal Employment Opportunity 5 Code: Field Unknown
eeo6code	Equal Employment Opportunity 6 Code: Field Unknown
eeoclass	Equal Employment Opportunity Class: Field Unknown
EEOJOBGR	Equal Employment Opportunity Job Grade: Field Unknown
eessno	Unique employee number
effdtdt	Effective date: Date for entry in database; typically refers to start date of current assignment
employee_id	Plant level employee id – Unusable variable
EMPSTATS	Employee Status: 0, I, J, N, O, X, or blank=Undefined 2=Short term disability 3=Long term disability 4=Terminated 5=Layoff 6=Leave of absence 7=Retired 8=Surviving spouse 9=Outside, not current A=Active D=Deceased L=Leave of absence P=Leave of absence with pay Q=Retired with pay R=Retired S=Suspended T=Terminated
EMPTYPE	Employee Type: H=Hourly E=Exception Hourly (we treat these as hourly) S=Salary
enddt	End date: The start and end date fields were created by Yale to reflect the beginning date of the HR entry (i.e. one day after the preceding entry for the same

	employee) and the day before the next HR entry for the same employee.
ETHNICDE	Employee Ethnicity Description
grade	Job Grade: Job grades for hourly and salary employees
GRADEABR	Grade Abbreviation
GRADEDES	Detailed grade description
hiredt	Hire date (see note at beginning of this document)
hourly_rt	Hourly Pay Rate
JOBCODE	Job Code: Field Unknown
JOBDT	Job Date: Field Unknown
jobgrnum	Job Grade Number: Field Unknown
JOBTITLE	Job Title: Detailed job title
JOBTLEAB	Job Title Abbreviation
LASTWORK	Last Day of Work: Field Unknown and Untested
locatcd	Location Code: 3-letter code
LOCATDES	Location Description: Plant/Location Name
monthly_rt	Monthly Pay Rate
PAYGRDES	Pay Grade Description (Monthly vs Hourly)
PAYGROUP	Pay Group: Field Unknown
PLANDESC	Plan Description: Field Unknown
REASONCD	Reason code: Abbreviated description of the ACTIONRS
REASONDE	Reason description: Detailed description of the ACTIONRS
recordid	Record ID: Concatenated field of eessno_effdtdt
rehiredt	Rehire Date
REVIEWRT	Field Unknown
ROWSOURC	Field Unknown
salplan	Salary Plan (seems to be part of GRADEDES)
servdt	Field Unknown
SEX	Employee Sex
shiftabrv	Shift Abbreviation: Field Untested
shiftdesc	Shift Description: Field Untested
shifttype	Shift Type: Field Unknown
startdt	End date: The start and end date fields were created by Yale to reflect the beginning date of the HR entry (i.e. one day after the preceding entry for the same employee) and the day before the next HR entry for the same employee.
STATUSAB	Status Abbreviation: Work status of employee; typically refers to EMPSTATS field
STATUSDE	Detailed Work Status Description: typically refers to EMPSTATS field

termdt	Termination Date

Appendix D: Medical/Drug Claims

Overview
This is the medical claims data for those employees participating in the company's medical plan. The data comes from the medical claims database.

Variable Descriptions:

Extract	Variable name	Brief description of variable
Professional	chg_allow_amt	Charge amount allowed
Professional	chg_submit_amt	Charge amount submitted
Professional	dx_cd	Diagnosis code
Professional	first_svc_dt	First date of service
Professional	last_svc_dt	Last date of service
Professional	mdst_place_cd	Location of service code
Professional	mdst_prov_type_cd	Provider type code
Professional	mdst_qty_svcs_cnt	Quantity of service rendered
Professional	net_pay_amt	Net amount paid
Professional	ntwk_prov_ind	Indicator as to whether provider was in the network
Professional	paid_dt	Date paid
Professional	person_id	Patient identifier
Professional	proc_cd	Procedure code
Professional	prof_proc_mod_cd_1	Procedure code modifier
Professional	prov_id	Provider identifier
Professional	third_party_amt	Third party amount
Professional	claim_id	Claim identification number
Professional	coinsurance_amt	Amount paid by co-insurance
Professional	copay_amt	Copay amount for employee
Professional	discount_amt	Discount amount based on health plan
Professional	family_id	Employee identifier
Drug	dtl_ther_class_cd	Detailed Therapeutic class code
Drug	gen_ther_class_cd	General Therapeutic class code
Drug	generic_id	Generic identifier
Drug	generic_name	Generic name

Drug	ndc_nbr_cd	National drug code
Drug	product_name	Product name
Drug	strength	Strength
Drug	person_id	Patient identifier
Drug	chg_allow_amt	Charge amount allowed
Drug	chg_submit_amt	Charge amount submitted
Drug	claim_id	Claim identification number
Drug	coinsurance_amt	Amount paid by co-insurance
Drug	copay_amt	Copay amount for employee
Drug	days_supply_cnt	Days of drug supplied
Drug	disp_fee_amt	Dispensing fee amount
Drug	net_pay_amt	Net amount paid
Drug	svc_dt	Date of service
Drug	rx_refill_nbr	Prescription refill number
Drug	dea_class_cd	Drug enforcement agency class code
Drug	manufacturer_name	Manufacturer name
Drug	pkg_qty_cd	Package quantity code
Drug	pkg_size_amt	Package size amount
Drug	product_cat_cd	Product category code
Drug	family_id	Employee identifier
Drug	paid_dt	Date paid