Comparison of facemask characteristics with user assessment of comfort

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COMPARISON OF FACEMASK CHARACTERISTICS WITH USER ASSESSMENT OF COMFORT

by

Matthew Purdy

A thesis submitted in partial fulfillment of the requirements for the Master of Science degree in Occupational and Environmental Health in the Graduate College of The University of Iowa

May 2019

Thesis Supervisor: Professor Patrick O’Shaughnessy
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This thesis is dedicated to my family, friends, and mentors. Thank you for supporting me in pursuing my academic goals.
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ABSTRACT

According to the Occupation Safety and Health Administration (OSHA), an estimated five million workers are required to wear respirators in over one million workplaces in the United States. Occupational respiratory diseases are strongly correlated to inhalation exposure to causative agents. Wearing a respirator has the potential to reduce worker exposure to safe concentrations. Many brands of N95 filtering facepiece respirators (FFRs) are available with various designs and sizes. Studies have indicated that respirator use is often low in many industries. Comfort is a factor that workers use both directly and indirectly to decide if they will wear an FFR. The purpose of this study was to evaluate ten N95 FFRs to determine their physical properties. Physical properties were compared to the perceived comfort ratings given by study participants to determine the strength of the associations. Six FFRs were evaluated using qualitative surveys (n=50).

Physical properties of FFRs that were evaluated include: breathability, pressure drop, surface area, water vapor transmission and weight. Several methods were used to evaluate the N95 physical properties. A modified American Society for Testing and Materials (ASTM) method was used to measure water vapor transmission. A pass through column apparatus was used to evaluate pressure drop through each sample at 0.6, 1.6, 2.6, and 3.6 LPM. The N95 FFRs were scanned and evaluated using Adobe Photoshop to determine surface area. A temperature probe was used to measure the influence of an exhalation valve on internal temperature. An inverted microscope was used to determine thickness, a balance was used to determine sample weight. Density could then be used to solve for solidity. Physical properties varied between N95 FFRs. Between two similar FFRs, the exhalation valve was attributed to a 0.59 °C lower
temperature in the FFR with and exhalation valve. Pressure drop values at a 3.6 LPM applied flow rate varied between 4.55-12.77 mm H₂O. The water vapor transmission between masks was very small with a range of 0.16 mg H₂O. Solidity values varied between 0.02 and 0.07, surface area from 134.95-313.87, and total weight from 9.47-109.41 g. The total scores varied from 10.76 to 14.26 (out of 18).

Survey participants were asked to evaluate the N95 FFRs on the basis of fit, temperature, and ease of breathing using a Likert scale of 1-6. Six of the N95 FFRs were worn by participants. Based on participant rankings, the Honeywell 4200 had the highest total score, followed by the Moldex 4200, 3M Aura 9210+, 3M 8511, Moldex 2200, and 3M 8210. The scores for fit varied from 3.16-4.36, temperature 3.66-5.24, and ease of breathing 3.94-4.66. Fit was found to be the most important in terms of discomfort followed by temperature, and ease of breathing.

The Kruskal-Wallis test results indicate that there is a significant difference in the median scores between masks types for fit, temperature, and ease of breathing (p<0.001). However, participants’ rankings of fit, temperature, and ease of breathing were not strongly related to a physical property. For example, the Spearman’s correlation coefficient between pressure drop and ease of breathing score was 0.2, and 0.6 for water vapor transmission and temperature. Neither Spearman’s coefficient was statistically significant (p=0.7, p=0.2).

In general, the differences in physical properties between N95 FFRs were too small for participants to perceive. The magnitude of difference in physical properties and short use duration and sedentary activity level are likely responsible for this finding.
PUBLIC ABSTRACT

An estimated five million workers are required to wear respirators in over one million workplaces in the United States. Occupational respiratory diseases are strongly correlated to causative agents. Wearing a dust mask has the potential to reduce worker exposures to an acceptable concentration. Many brands dust masks are available with various designs and sizes. Studies have indicated that dust mask use is often low in many industries. Comfort is a factor that workers use both directly and indirectly to decide if they will wear a dust mask. The purpose of this study was to evaluate ten N95 FFRs to determine their physical properties. Physical properties were compared to the perceived comfort ratings given by study participants to determine the strength of the associations. Six FFRs were evaluated using qualitative surveys (n=50).

This study evaluated ten dust masks to determine their physical properties. Physical properties were then compared to the perceived comfort ratings given by participants (n=50) for six of the dust masks. Physical properties of dust masks that were evaluated include: breathability, pressure drop, surface area, and weight. Physical properties varied between dust masks. Fit was found to be the most important in terms of discomfort followed by temperature, and ease of breathing. However, participants’ rankings of fit, temperature, and ease of breathing were not strongly related to a physical property. In general, the differences in physical properties between dust masks were too small for participants to perceive. This also may be influenced by the trial durations and sedentary activity level.
# TABLE OF CONTENTS

LIST OF TABLES ........................................................................................................... ix
LIST OF FIGURES ......................................................................................................... x

CHAPTER I: LITERATURE REVIEW .............................................................................. 1
  Overview ..................................................................................................................... 1
  Inhalation Hazards ..................................................................................................... 3
  Respiratory Illnesses .................................................................................................. 3
  Hazard Control Strategies .......................................................................................... 4
  Personal Protective Equipment (PPE) ........................................................................ 5
  Respirators ................................................................................................................ 5
  N95 Filtering Facepiece Respirators (FFRs) ............................................................. 6
  N95 FFR Comfort ........................................................................................................ 8
  Respiratory Protection Programs ............................................................................... 9
  Respirator Use Surveys ............................................................................................. 10
  Factors Influencing Respirator Comfort and Use ....................................................... 10
  Shortcomings of the Literature ................................................................................ 13
  Specific Aims .............................................................................................................. 13

CHAPTER II: ASSESSMENT OF USER COMFORT IN RELATION TO RESPIRATOR CHARACTERISTICS ................................................................. 15
  Introduction ............................................................................................................... 15
  Methods ..................................................................................................................... 17
    Pressure Drop Measurements .................................................................................. 17
    Water Vapor Transmission - ASTM E96 ............................................................... 20
    Solidity (α) .............................................................................................................. 22
    Surface Area .......................................................................................................... 23
    N95 FFR Internal Temperature ............................................................................... 23
    N95 FFR Qualitative Surveys .................................................................................. 23
    Statistical Methods ................................................................................................. 25
  Results ....................................................................................................................... 26
  Discussion .................................................................................................................. 29
    Limitations .............................................................................................................. 35
  Conclusion .................................................................................................................. 37
LIST OF TABLES

Table 1. Percent of total pressure drop contributed to by the filter layer. .................. 43

Table 2. The slope values* are listed for the unadjusted pressure drop measurements for the all layers and the separated filter layer. ................................................................. 44

Table 3. Solidity, total weight, surface area, pressure drop, and water vapor transmission of ten N95 FFR types. .......................................................................................... 45

Table 4. Average and total scores for survey questions one, two, and three across six N95 FFR types. ........................................................................................................ 47

Table 5. Question four qualitative responses were coded as numbers for data analysis. . 48

Table 6. Effect of exhalation valve on internal FFR temperature. ................................. 52

Table 7. Dunn’s test of question one (fit) responses across six different N95 FFRs, and median scores. .......................................................................................................... 53

Table 8. Dunn’s test of question two (temperature) responses across six different N95 FFRs, and median scores. .............................................................. 54

Table 9. Dunn’s test of question three (ease of breathing) responses across six different N95 FFRs, and median scores. .............................................................. 55

Table 10. Participant facial measurements. ................................................................. 56
LIST OF FIGURES

Figure 1. Average pressure drop measurements from the separated filter layer of ten different N95 FFR types performed at four different flow rates. ........................................... 39

Figure 2. Average pressure drop measurements from samples containing all filter media layers of ten different N95 FFRs at four different flow rates. ................................. 40

Figure 3. Average pressure drop measurements from the separated filter layer of ten different N95 FFR types performed at four different flow rates. Flow rate values were corrected for differences in surface area between the N95 FFRs. ......................................... 41

Figure 4. Average pressure drop measurements from samples containing all filter media layers of ten different N95 FFR types at four different flow rates. Flow rate drop values were corrected for differences in surface area between the N95 FFRs. ...... 42

Figure 5. Distribution of survey responses for questions one, two, and three across six different N95 FFRs. ................................................................. 46

Figure 6. Question four responses separated by question and N95 FFR numbers. ....... 49

Figure 7. Cumulative count of responses for question four separated by responses choice. ......................................................................................... 50

Figure 8. Comparison of survey responses between N95 3M 8210 (no exhalation valve) and 3M 8511 (exhalation valve). ......................................................... 51
CHAPTER I: LITERATURE REVIEW

Overview

According to the Occupational Safety and Health Administration (OSHA), an estimated five million workers are required to wear respirators in over one million workplaces in the United States. Occupational respiratory diseases are strongly correlated with exposure to causative agents. Wearing a filtering facepiece respirator (FFR) has the potential to reduce worker exposure to concentrations below recommended exposure limits. FFRs are approved by the National Institute for Occupational Safety and Health (NIOSH) to provide a minimum level of protection against airborne particulates. N95 FFRs are a specific type of FFR that is approved to provide a minimum of 95% capture of non-oil particulates that are 0.3 micrometers in size. Studies have indicated that respirator use compliance is often low in many industries. Comfort is a factor that workers use both directly and indirectly to decide if they will wear a N95 FFR. Employers currently have minimal data available to select N95 FFRs with qualities most associated with comfort.

Prior research surrounding respirator use and comfort have been qualitative and often do not disclose the respirator models used in each study. Studies have also helped to define the overarching problem of employee dissatisfaction with respirator comfort and the subsequent low use compliance. Additionally, studies have identified key areas influencing respirator comfort which include: temperature and humidity, breathing difficulty and facial comfort. Laird et al., (2002) suggests that increased temperature in the thermosensitive cheek area of nearly half of the participants could be a significant cause of discomfort. Physical characteristics of respirators that are most
related to prior determinants of comfort include: weight, breathability, pressure drop, and physical construction. The N95 FFR internal environment contributes to comfort due to elevated relative humidity and temperature. However, these studies have still left the question as to the magnitude of difference between N95 FFR brand and models in terms of measurable physical characteristics of comfort.

This study evaluated the measurable physical properties of N95 FFRs to determine which model performs the best in areas associated with comfort including: weight, breathability, vapor transmission, and pressure drop. Although comfort is often a subjective term, physiological responses in the body including increased heart rate, changes in blood pressure, difficulty breathing, and increased facial temperature demonstrate that respirators clearly affect the human body.\(^7\-\(^9\) Differences in measurable body parameters with and without a respirator being worn indicate that wearing a respirator is responsible for the observed changes.\(^9\) Therefore, since differences exist between the measurable physical properties of respirators, physiological responses should also vary. Subsequently, a difference should exist in the perceived comfort. Relative humidity and temperature influence comfort. ANSI/ASHRAE Standard 55-2013: “Thermal Environmental Conditions for Human Occupancy” recommends an indoor temperature range from 68.5 °F and 80.5 °F depending on the month of the year. Additionally, the indoor relative humidity should be maintained at or below 65%.\(^10\) N95 FFRs can increase the temperature and humidity against the users’ face causing them to be outside of the recommended range. Lastly, psychological consideration should be made in evaluating respirator comfort as users may experience anxiety.\(^11\).
Inhalation Hazards

Aerosols are a major hazard that adversely affect the respiratory system. Aerosols are a suspension of particles or droplets in a gaseous medium. Specifically, particulate matter, dust, fumes, and bio-aerosols are major respiratory health concerns across many industries. Processes involving grinding and crushing are often associated with the generation of particulate matter. Bioaerosol hazards may be present in industry sectors such as agriculture and healthcare. Bioaerosols are created when biological particles are suspended into the air.

Respiratory Illnesses

Exposure to airborne contaminate can lead to illnesses that are restrictive, obstructive, and/or cancerous. The resulting illness and severity are dependent on the type of agent along with exposure characteristics including concentration, duration and frequency of exposure, and fraction absorbed.

According to NIOSH, more than 20 million workers are potentially exposed to occupational agents that are capable of causing chronic obstructive pulmonary disease (COPD) and asthma. Nine million of these workers are exposed to agents associated with asthma. Approximately 28% of adult asthma cases can potentially be attributed to workplace conditions.\(^{(12)}\) Existing asthma may worsen due to occupational exposures. Pneumoconioses are responsible for over 1,500 deaths per year.\(^{(13)}\) NIOSH also estimates that occupational asthma costs approximately $400 million each year in the United States.

Agricultural workers with a history of working with livestock experience excess risk of developing respiratory illnesses compared to the general public. Respiratory diseases among workers are caused by exposure to organic dust, particulates and
microbial cell wall components. As a result of exposure, biological pathways are activated resulting in a complex biological response in the lungs.\(^{14}\) Hoppin et al. determined that acute symptoms including wheeze, cough, and phlegm are more common among farmers while shortness of breath and chronic cough and phlegm are more common in the general public. According to (Poole et al., 60% of swine veterinarians reported rhinitis symptoms.\(^{17}\) Additionally, 67% of farmers reported rhinitis with 39% having three or more episodes of rhinitis in the past year.\(^{18}\) Farmers are also at excess risk for hypersensitive pneumonitis and toxic organic dust toxic syndrome. When people who do not work in agriculture entered a barn over a short exposure period, indication of inflammation was apparent to researchers shortly after.\(^{19}\)

**Hazard Control Strategies**

Occupational respiratory diseases are strongly correlated to causative agents. There are several control options capable of reducing worker exposure to hazards. The hierarchy of controls is a systematic approach used to reduce workplace exposures. From the most to least preferred, the hierarchy of controls recommends: elimination, substitution, engineering controls, administrative controls, and lastly PPE. When the hazardous agent cannot be eliminated or substituted, engineering controls alone or in combination with personal protective equipment (PPE) may reduce exposure to acceptable concentrations. Engineering controls are often in the form of local exhaust ventilation (LEV) and general exhaust ventilation (GEV). LEV systems are used when the contaminant is highly toxic or produced at a single point. GEV systems are used to reduce contaminant concentrations with low toxicity. Additionally, administrative
controls can be used to reduce employee exposure. This administrative approach can involve rotating employees performing a task with significant exposures.

**Personal Protective Equipment (PPE)**

PPE encompasses protective clothing and devices that can be worn by a worker to reduce or eliminate exposure to a hazard. PPE should be selected to ensure that it can adequately protect against the hazards that are present. The selected PPE should not introduce any new hazards. Once the appropriate PPE is selected, a program should be created regarding its use in the workplace which will outline PPE training, maintenance, and proper use. PPE is generally provided at no cost to the worker when it is required by the employer. Common PPE include: respirators, steel toe boots, safety glasses, gloves, hard hats, and high visibility clothing.

**Respirators**

Respirators can be classified as either atmosphere-supplying or air-purifying. They can be further classified into tight-fitting and loose-fitting.\(^{(20)}\) Tight fitting respirators seal to the user’s face forcing contaminated air to be filtered before being inhaled. Tight fitting air-purifying respirators have negative pressure relative to the exterior environment during inhalation. Atmosphere-suppling respirators deliver clean air to the user and are the only type of respirator suitable for immediately dangerous to life or health (IDLH) conditions. Specifically, a pressure demand atmosphere-suppling respirator is required. Filtering facepiece respirators, half masks, powered air purifying respirators (PAPR), and full facepiece respirators are types of air purifying respirators. However, only half mask and full facepiece respirators can be used with cartridges that
provide protection from chemical hazards. Atmosphere-supplying respirators include supplied-air respirators (SAR) and self-contained breathing apparatus (SCBA).

**N95 Filtering Facepiece Respirators (FFRs)**

OSHA uses the term filtering facepiece respirator (FFR) to describe what is otherwise commonly referred to as a disposable dust mask (OSHA Respiratory Protection Standard, 1910.134). OSHA defines an FFR as a negative pressure particulate respirator with a filter as an integral part of the facepiece or with the entire facepiece composed of the filtering medium. In addition to the filter media, FFRs typically consist of additional supporting layers that are held onto a worker’s face with elastic straps. The number of layers varies based on brand and model. However, most FFRs consist of one or two structural layers, a pre-filter layer, and a filter layer. Likewise, FFRs may have one or two straps. FFRs come in three types including: N (non-oil), R (resistant), and P (proof) types indicating the degree of protection from oil based particles. FRRs are then classified by their protection from particulates. NIOSH approves FFRs regarding their level of protection from particulates 0.3 micrometers or larger. FFRs are approved as either 95 (95% filtration), 99 (99% filtration), or 100 (99.97% filtration).

The particle removal effectiveness of an N95 FFR is approved by NIOSH using methods established in 42 CFR Part 84 to remove at least 95% of non-oil particles that have an aerodynamic diameter of 0.3 micrometers. This is the particle size for which FFRs have a minimum capture efficiency. N95 FFRs do not provide protection from chemical hazards including vapors and gasses. Particles are captured through impaction, interception, and sedimentation. These processes allow filter fibers to collect particles and prevent them from entering the human respiratory system. N95 FFRs are often available
in three sizes: small, medium, and large. Additionally, one-size-fits-all N95 FFRs are also commonly available. N95 FFRs are considered by NIOSH to be a respirator. This should not be confused with surgical or other masks which are not respirators as they are not approved regarding their protective capabilities.

PPE including N95 FFRs should not be the first control option to reduce worker exposure. According to the OSHA Technical Manual, FFRs are only effective when worn as intended, and correctly selected for the appropriate hazard.\(^{(22)}\) N95 FFRs are also beneficial in instances where nuisance dust is present below OSHA permissible exposure limits (PELs), which may not be protective enough for all workers. However, OSHA also designates FFRs as having an “Assigned Protection Factor” of 10, which means that when worn properly, an FFR is expected to reduce exposures ten-fold. N95 FFRs are beneficial where hazards cannot effectively or feasibly be controlled with engineering controls. Instances include: agricultural environments, construction, and gas metal arc welding where the protective shield gas will be removed when oxidizing a new weld.

Research is currently being conducted to control airborne contaminants in swine and poultry operations. However, PPE is currently the standard for protection in these environments. Engineering controls are expensive to design, implement, and maintain. Therefore, N95 FFRs offer a low-cost solution. Animal, vehicle, and human movement can suspend dust and associated bio-aerosols when moving throughout a farm. It is often not feasible to control excessively large areas with numerous sources of exposure. Outdoor environments have limited control options. When working on a large construction site or farm, N95 FFRs allow workers to be protected from airborne contaminants.
N95 FFRs would be effective for chronic exposures to low hazard airborne contaminants. Contaminants including asbestos and silica should be controlled with alternative respirator types when prolonged or frequent exposure is anticipated. This study will help to identify physical properties of respirators that are expected to be perceived as comfortable. The findings may lead to increased use in both voluntary and non-voluntary respirator programs.

**N95 FFR Comfort**

N95 FFRs are often considered uncomfortable and are therefore not worn by workers. (3, 4) Physiological and psychological responses occur in the body as a result of N95 FFR use. (9) The extent that a N95 FFR will affect a worker’s perception of comfort is related to its physical properties. N95 FFRs which minimally alter a worker’s respiratory function and facial environment should be considered more comfortable. Differences are present in the construction and physical properties of the N95 FFR. If the variation in the selected measurable physical properties are large enough then workers should be able to detect comfort differences between the face masks. Selecting a N95 FFR that has minimal impact on worker comfort may increase use and reduce exposure to airborne contaminants. Increased use has the potential to reduce the burden of respiratory illnesses. This study will act as a resource to inform employers and employees of the differences between various N95 FFR brands and models that influence their comfort. Additional data will enable the types of N95 FFRs to be purchased that are most suitable for their specific needs while ensuring optimal comfort and use.
Respiratory Protection Programs

Both private and public organizations have established standards for respiratory protection. OSHA has developed enforceable standards which are located in 29 CFR 1910.134. This standard outlines types of respiratory protection and instances where they are appropriate. For non-voluntary respirator use, employers are required to develop a respiratory protection program which requires training employees regarding: when to use the respirator, donning and doffing procedures, maintenance, storage, and replacement. A medical evaluation is also required. A hazard assessment must be completed before selecting respiratory protection in a non-voluntary use workplaces. Workers are not permitted to have facial hair as it interferes with the respirator seal. Next, the worker must pass OSHA-approved quantitative or qualitative fit testing as they are using a negative pressure respirator. Once a suitable respirator is selected the worker must perform a user seal check to ensure that there are no leaks. Assigned protection factors are used as a multiplier of the permissible exposure limit (PEL) to determine the concentrations that respirators may be used at. PEL values are legally enforceable concentrations for contaminants that are set by OSHA to protect worker health. The American National Standards Institute also creates respirator standards (ANSI). However, ANSI standards are not enforceable.

In instances where respirator use is voluntary, a comprehensive program may not be needed if N95 FFRs are being used. In many industries, including agriculture, workers may be exposed to nuisance levels of contaminants that are below the OSHA PEL. They may choose to wear a respirator, which is often a N95 FFR. PPE should only be selected in situations where engineering controls are not feasible. (21) For both voluntary and non-
Respirator Use Surveys

Survey studies across several industries indicate that respirators have been considered uncomfortable to wear by workers.\(^{(3, 4)}\) Although respirators are required under CFR 1910.134 to protect workers from airborne hazards in instances where they cannot be controlled to remain below the PEL, workers may refuse to wear their respirators due to design parameters. In a study of California agricultural workers, the average response regarding personal protective equipment (PPE) for dust protection varied between “rarely” and “less than half the time”.\(^{(2)}\) In a study of construction workers approximately 49% did not wear respirators at construction sites regularly.\(^{(23)}\) Aside from risk perception, availability, and job hindrance, comfort is expected to be a cause of worker noncompliance. In a study of automotive workers 62% rated their respirator as uncomfortable.\(^{(4)}\) Only 30% of swine workers reported using a respirator while inside the barn.\(^{(24)}\)

Factors Influencing Respirator Comfort and Use

Overall, respirator comfort is a function of its physical properties and the physiological and psychological outcomes that these properties have on the user across various work intensities and durations. Prior research has suggested that added inspiratory and expiratory breathing resistance, dead space, and weight have the greatest influence on work capacity. Physiologically effects include: changes in breathing patterns, hypoventilation, retention of carbon dioxide, and increased breathing effort.\(^{(7)}\) A dose-response relationship was found between exercise intensity and heart rate. However,
the group wearing respirators experienced a greater rate of heart rate increase than those without a respirator. This effect is most predominate during high exertion exercises.\(^9\)

Evaluating the differences in respirator physical properties provides criteria to select a respirator with minimal physiological effects on the body which may be perceived as more comfortable. Jones (1991) also found a biphasic effect on systolic blood pressure where it is lower at rest and higher at high levels of exertion.\(^9\) A N95 FFR evaluation study of healthcare workers found that air in the face mask dead-space oxygen and carbon dioxide levels did not meet OSHA’s ambient workplace standards.\(^{25}\) Quantitative analysis in this study will allow a better comparison of face masks and act as a predictor of physiological and psychological outcomes on the user. Qualitative methods may help to demonstrate whether or not the user can perceive the measured differences between masks.

Niezgoda et al., suggests that fold flat face masks have the potential to be more comfortable than cup face masks.\(^{16}\) Fold flat face masks in this study were found to have lower seal pressures than cup face masks while maintaining a similar fit factor. Although this is not conclusive evidence as differences exist between brands and models, therefore both face mask types will be evaluated in this study.

Popendorf et al., identified areas of mask comfort that are a concern to agricultural workers.\(^{6}\) This includes: breathing ease, skin comfort, weight, fit, convenience, and internal temperature and relative humidity. These data helped to determine the physical properties of the face mask that would be evaluated in this study which include: water vapor transmission, pressure drop, temperature, and relative humidity.
Wearing a face mask increases facial temperature which is a thermosensitive area of the body. One study found air temperatures inside a respirator to be on average 7.5 °C warmer than subjects without respirators across various work intensities. Laird et al. (2002) found 11 of the 12 participants had increased lip temperature while 4 out of the 12 participants had increased cheek temperature. Exhalation valves can be used to increase ease of breathing and reduced heat buildup. Additionally, a study evaluated the thermal differences between two similar respirators that only differ due to the presence of an exhalation valve. The skin temperature under the mask without the exhalation valve was approximately 1°C higher than the face mask with the exhalation valve. A randomized open-label controlled crossover design study of adult male military personnel performing prolonged essential outdoor duties found that masks with an exhalation valve provided greater comfort and exertion than those without an exhalation valve.

Psychological consideration should be made when evaluating comfort. This may be caused by the pressure of the face mask on the user’s face which is a sensitive area of the body. A survey of healthcare workers revealed that respirators may contribute to claustrophobia, difficulty breathing, and dizziness. One study suggests that sensitivity to pressure does exist across the face, but not significantly enough for design changes to be recommended. However, Kim et al. (2015) suggest that that nose bars in the face mask can distort the nasal alae increasing nasal resistance and breathing effort which may cause the user to switch to oral or oronasal breathing. Nasal breathing is preferred to oral breathing as there are physiological benefits. They suggested that face seal adhesives or pre-molded nasal contours could be explored to help overcome this issue.
**Shortcomings of the Literature**

Physiological and psychological effects have been identified as attributable to respirator properties and comfort. However, the disclosure of brand, model, and size used in testing are often unknown; specifically for N95 FFRs. In large scale qualitative surveys the researchers themselves may be unaware of this data. Duration of FRR use, ambient condition, and extent of exertion influence the findings of respirator studies. Surveys containing Likert scales have been useful in determining that FFRs are considered uncomfortable and in selecting physical properties of interest. However, this has not been commonly used to conduct a side by side comparison between FFRs. Studies which modify only a single design parameter such as pressure drop are valuable in determining thresholds of perception.\(^{32}\) However, when selecting a N95 FFR it is likely that several physical properties or the N95 FFR design will be different from one another. N95 FFR comfort is influenced by several factors in combination with one another. Comfort is therefore a function of physiologic and psychologic effects that the N95 FFR has on a user which are determined by its physical properties. Employers may currently have difficulties differentiating N95 FFR comfort due to a lack of comparison studies. There is a need for a study to conduct a comprehensive side by side comparison of N95 FFRs on the basis of physical properties and perceived comfort.

**Specific Aims**

Discomfort is a contributing factor to low N95 FFR use. Low use has the potential to leave workers unprotected from airborne contaminants. The goal of this study is to evaluate the physical properties of N95 FFRs that are associated with comfort. This goal will be assessed by completion of the following specific aims:
1. Evaluate the physical properties of N95 FFRs associated with comfort.

2. Determine the strength of association between N95 FFR physical properties and user perception of comfort.

This information will be used to determine associations between respirator physical properties and user perception of comfort. The study rationale is that through a better understanding of the physical properties driving N95 FFR comfort, use will increase, therefore reducing the burden of airborne contaminants on worker health. The results of this study will serve as an advisory for employers looking to adopt evidence-based recommendations to improve their respirator program and maximize worker use of N95 FFRs. Increases in N95 FFR use can be achieved through informed purchasing practices of employers, the adoption of stricter design criteria by manufactures, and worker satisfaction with the N95 FFR.
CHAPTER II: ASSESSMENT OF USER COMFORT IN RELATION TO RESPIRATOR CHARACTERISTICS

Introduction

Millions of workers are required to wear a respirator in the United States.\(^1\) N95 filtering facepiece respirators (FFRs) are approved to prevent airborne contaminants from entering the lungs. Reducing exposure to airborne contaminants decreases the likelihood of developing adverse health outcomes including: pneumoconiosis, asthma, and COPD.\(^{33}\) N95 FFRs are widely available and offer an inexpensive control to protect workers. However, N95 FFRs should be the last choice option as elimination, substitution, and engineering controls are preferred.\(^{21}\) The OSHA technical manual suggests that N95 FFRs need to be worn in a correct manner to ensure the worker is protected. Considerations include: ensuring proper fit, medical evaluation, worker use compliance, and a respirator program.\(^{22}\)

N95 FFRs can also be used voluntarily to reduce exposure to nuisance level contaminants that are below the permissible exposure limit (PEL). Agricultural settings are an example of a workplace where it may benefit workers to wear a FFR even when concentrations of contaminants do not exceed the OSHA PEL.\(^{34}\) For example, the OSHA PEL can be below the NIOSH recommended exposure level (REL). For grain dust the PEL is 10 mg/m\(^3\) and the REL is 4 mg/m\(^3\). NIOSH suggests that grain dust concentrations below the PEL can still cause symptoms which may include: cough, wheezing discomfort, aggravated asthma, eye and nasal irritation.\(^{35}\) Workers may feel more comfortable reducing their exposure to dust and other airborne hazards through the use of a FFR.\(^{36}\) Farm conditions are often variable and it can be difficult to evaluate and control exposures over a variety of indoor and outdoor environments.
The use of respirators, including N95 FFRs has been determined to be low across many industries.\(^{(2, 23)}\) Although risk perception and respirator availability may affect use, discomfort has been commonly reported among workers who use N95 FFR.\(^{(6)}\) N95 FFR discomfort is caused by the physiological and psychological effects that they have on workers.\(^{(11)}\)

Differences exist in the physical properties, construction, and design between different N95 FFR brands and models. Studies have identified that elevated temperature, humidity, breathing resistance, fit, and weight contribute to user discomfort.\(^{(11)}\) Using laboratory analyses N95 FFR physical properties related to discomfort can be measured. Properties of interest in this study include water vapor transmission, weight, and pressure drop. A qualitative survey method can be used to evaluate the user’s perception of fit, temperature, and ease of breathing. Other studies have evaluated FFR comfort using survey methods, however they often do not control for N95 FFR type, brand, and model.\(^{(3, 4, 6)}\) Individual properties have also been evaluated to determine their influence on comfort.\(^{(32)}\) Furthermore, although Seng et al. suggest that exhalation valves contribute to ease of breathing and comfort, additional material differences have not been disclosed to aid in the selection of a N95 FFR.\(^{(28)}\) However, the extent that physical material properties contribute to the perception of comfort by the user is unclear.

The purpose of this study was to evaluate the physical properties of N95 FFRs that have been related to comfort. Associations were evaluated between the physical properties measured in a laboratory setting and perceived comfort of participants wearing the N95 FFR. This study is intended to determine the importance of material physical properties in relation to comfort.
Methods

The N95 FFRs selected for analysis were most commonly cup shaped and semi-rigid. A seam is present in many of the cup shaped N95 FFRs where fabric is fused together. Several fold-flat respirators were also used. They have a seam down the middle which allow the N95 FFR to open and fit against the user’s face. The FFRs are made of several layers of material. Usually a filter, pre-filter, and structural layer is present in most of the N95 FFRs. One or two straps made of elastic or stretchable plastic are stapled/glued to the N95 FFR to secure it onto the user’s head. Some respirators have an exhalation valve and/or nose clip.

Ten N95 FFRs were selected for analysis that represented a variety of different design features that have the potential to affect comfort. The Honeywell 4200 is an elastomeric style N95 respirator with replaceable filter media pieces and an exhalation valve. The 3M 8210, 3M 8511, Moldex 2200, Moldex 2300, Moldex 4200, and Dentec ADN95A are cup shaped N95 FFRs. The 3M 8511 has an exhalation valve. The Moldex 4200 is comprised of repeating folds, and has a large surface area. Both the Moldex 2200 and 4200 have a semi-rigid plastic support layer on the outside (thick) and inside (thin) of the FFR. RZ Mask F2 Filter is a combination of a filter media that is inserted into a neoprene facemask. The RZ mask is not N95 approved by NIOSH. The 3M Aura 9210+ and Dentec AD4N95 have a fold flat design. The RZ Mask with F2 filter, all Moldex models, and Honeywell 4200 do not use nose bars.

Pressure Drop Measurements

Ten FFRs were evaluated to determine pressure drop, a material property that is related to ease of breathing. Pressure drop in this analysis is the measure of the change in
pressure created by an N95 FFR sample. Pressure drop is determined using a sensor which subtracts the pressure measurements taken on each side of a sample. A pass-through column with a 2.7 cm inner diameter was used to hold FFR samples securely in place so that air from above the sample can only move through the column by directly passing through the FFR sample. This column is one part of a more complex setup used to evaluate pressure drop through the FFR material. The column was designed individually for experiments evaluating FFR samples. Circular samples were small enough to fit flush in the pass-through column and were cut out of the N95 FFRs. Seams on the masks were avoided, along with areas that are not representative of the N95 FFR. The samples were held securely between an O-ring embedded on the bottom half of the column, which pressed against the top portion of the column. Wing nuts were tightened to compress the top and bottom pieces of the column. Plastic tubes were used to connect supply air to the column. A valve was used to adjust flow rate.

A previous study determined the respiratory minute volumes from approximately the fifth percentile female at 40% work rate (of maximum exertion) to the ninety fifth percentile male at 80% work rate to range between 21-118 liters per minute (LPM) \(^{(37)}\). Four flow rates were used to cover this range of minute volumes. These values were extrapolated based on the surface area of a 3M 8514 FFR relative to the surface area of the filter media sample in the pass-through column to determine the flow rates needed through the column. This yielded flow rates of 0.6 LPM, 1.6 LPM, 2.6 LPM, and 3.6 LPM, which were selected to be used in this study.

To begin a trial, a sample from a mask was put into the pass-through column and secured in place. A primary standard (Gilibrator 2 bubble meter) (Clearwater, FL) was
used to calibrate the flow rate for each trial. Moving air through the outside of the mask simulates the inhalation of air. Flow rates were applied from low to high. A Dwyer Series 646B differential pressure sensor (Michigan City, IN) was used to measure the pressure drop through each sample. Pressure taps and related tubes connected above and below the sample on the pass-through column, were attached to the pressure sensor. This allowed the pressure drop to be measured. A calibration curve was created to convert the electrical signal from the sensor into a pressure measurement. Three samples from each mask type were performed, with each sample coming from separate unused masks. Overall, three trials were performed for each mask type across four flow rates for one minute each. Therefore, ten mask types were sampled, with three samples each over flow rates for a total of 120 trials. Trials were performed for both FFR samples types, only the filter layer and all layer samples. This test was performed again using only the filter layer, with three samples being used for each N95 FFR type. LabVIEW 2017 software (National Instruments, Austin TX) was used to data-log pressure measurements over the one minute sampling durations. This program converts the electrical signal from the instrument into a value that is applied automatically into a calibration curve equation. The resulting data is in units of mm H$_2$O, and was analyzed using Microsoft Excel to compute descriptive measures and graphs.

The flow rate at each pressure drop measurement was normalized to compensate for differences in FFR surface area. This adjustment was necessary as the four flow rates used in this study assumed the same surface area for each FFR. The following equation was used to normalize the pressure drop data for each FFR.

\[ Q_m = \frac{A_m}{A_c} Q_c \]
Where $Q_m$ is flow rate through the mask, $Q_c$ is the flow rate through the column, $A_m$ is the area of the mask, and $A_c$ is the area of the inner hole of the column.

**Water Vapor Transmission - ASTM E96**

*Method Overview:*

The American Society for Testing and Materials (ASTM) method E96 was the basis for the procedure used in this study (38). The purpose of this method is to evaluate the amount of water that passes through a FFR sample in a controlled environment. This modified method involves blowing dry air at a set flow rate over a FFR sample sealed over a cup-shaped apparatus containing water in an enclosed chamber. As explained further below, the difference in pre- and post-weights was calculated to determine the amount of water vapor transmission.

*Experimental Setup and Procedure:*

The setup involves a metal box with two holes, one for incoming and the other for outgoing air. A third hole is for a TSI 7545 meter (TSI Inc., Shoreview, MN), an instrument capable of measuring temperature and relative humidity. Tape was used to mark the location where the apparatus containing the sample should be placed. This location ensures the flow rate across each sample is the same, as only one trial can be run at a time.

The apparatus used in this study was a Thwing-Albert EZ-Cup Vapometer Permeability Cup (3/4” EZ-Cup) (West Berlin, NJ), which is specifically designed for ASTM E96. The apparatus is cup-shaped and is made of two main pieces, a flanged cup and a lid. Both are constructed of aluminum. The bottom portion of the cup is flanged,
allowing an approximately 3/4” circular sample to be placed here. This piece held 15 mL of deionized water which was measured using a graduated cylinder. The top piece is a hollow aluminum ring that holds the perimeter of the sample in place. Both pieces are threaded, allowing them to be twisted together, clamping the sample in-between. The flanged cup piece and hollow top piece allow the sample to be directly over the water in the cup, and unobstructed from air flowing over the sample. Teflon and rubber gaskets above and below the sample create a tight seal as the cup and upper ring are twisted together. Therefore, the only way for the water to escape the apparatus is by moving through the FFR sample (membrane). There is space between the sample and water, preventing contact that may influence the results. Trials were run with a constant flow rate and supply air properties (% RH and temperature).

Trials were run with a constant flow rate of 10 LPM and supply air properties were approximately 21º C and 4.5% for all of the trials. A TSI 4000 series flow meter (TSI Inc., Shoreview, MN) was used to set the flow rate of incoming a supply air. Positive pressure is created inside of the box, preventing ambient air from entering.

The trial durations were one hour long. During the trial, air flowed over the sample causing water vapor to move across the FFR sample. The entire sample apparatus was weighed at the beginning and end of each trial. The difference in pre- and post-weight was the amount of water that moved through the FFR. This method was used to measure the vapor transmission through nine of the ten N95 FFRs. The RZ mask (F2 filter) consists of filter media that is inserted into a neoprene facemask; this could not be cut to an appropriate size for this method.
Solidity

Solidity is the density of the filter media relative to the density of the media if it were solid, having no air pockets. Solidity is a commonly-used property of filter media and is analogous to the concept of “porosity”, which indicates the amount of void space between fibers, so that solidity = 1 – porosity. The following steps were used to determine the solidity of the filter layer for each N95 FFR. Three 15.65 mm diameter samples were cut out of each N95 FFR using a hole punch. The samples were then weighed using a balance. Solidity of the filter layer is calculated using the mass, volume, and density of a sample. Most N95 FFR filters are made of polypropylene.

To begin solidity analysis, three rectangular samples were cut from each of the ten N95 FFRs filter layers. An inverted microscope was used to view the bottom edge of each sample. A phone mount was attached to the microscope eyepiece to allow pictures to be taken of the mask samples. The photos were analyzed in Image J, a shareware program developed by the National Institute of Health that can be used to measure sample thickness. The average thickness and weight of each N95 FFR sample triplicate was used in subsequent calculations to calculate solidity, $\alpha$, using the following equations:

$$\alpha = \frac{\rho_f}{\rho_T}$$

where:

$$\rho_f = \frac{m_f}{\frac{\pi d^2}{4} \cdot L}$$

and

$$\rho_T = \text{density of polypropylene (}0.855 \text{ g/cm}^3\text{)}$$

with other terms defined as following:

- Measured density of the sample media ($\rho_f$)
- Measured mass ($m_f$)
Respirator media thickness (L)

Diameter of circular portion of respirator media (d)

**Surface Area**

Several incisions were made into the N95 FFRs allowing them to lie flat on a document scanner. A piece of cardstock paper was placed behind each N95 FFR on the scanner to secure and flatten them. The scanned N95 FFRs documents were then analyzed using Adobe Photoshop to obtain the surface area. A United States penny was used as a scale for the FFR scans, this coin’s diameter is 19.05 mm.

**N95 FFR Internal Temperature**

A TH-40000 Series fast response thermistor (temperature sensor) (Norwalk, CT) was used to measure the temperature inside of the 3M 8210 and 3M 8511 N95 FFRs. This probe was placed inside of the FFR, between the face and FFR. A calibration curve was created by measuring several temperature using a TSI 7545 temperature meter (TSI Inc., Shoreview, MN) as a standard. These two FFRs have many similarities. However, the 3M 8511 has an exhalation valve. This test was intended to evaluate the effect of an exhalation valve on internal temperature. Two trials of one minute durations were used for both N95 FFRs. Measurements were collected using LabVIEW 2017.

**N95 FFR Qualitative Surveys**

Qualitative analysis was performed on six of the ten N95 FFRs. The FFRs that were selected include: Moldex 2200, Honeywell 4200, 3M 8210, 3M 8511, 3M Aura 9210+, Moldex 4200. A subset of FFRs with different designs were selected to make comparisons rather than selecting similar-looking masks. The 3M Aura 9210+ is a fold
flat FFR. The 3M 8210 and 8511 are both cup shaped, however the 3M 8511 has an exhalation valve. Both Moldex FFRs use webbing as a structural layer. The Moldex 4200 was unique in that it has a series of repeating folds which increase surface area. The Honeywell 4200 is an elastomeric style facemask with an insertable N95 media. The other four FFRs used in this study were excluded for participant trials due to redundancy in design, appearance, and cost of purchasing additional materials.

A four-question survey was developed to evaluate the comfort of N95 FFRs while worn by the participants (see Appendix A). A Likert scale (1-6) was used for evaluating three questions concerning the degree to which temperature, ease of breathing, and fit against the face influenced the user’s perception of comfort. A score of one indicates the most uncomfortable choice, where a score of six indicates the most comfortable (similar to no FFR is being worn). A fourth question asked participants to identify which of the three FFR properties was most important in terms of discomfort. The survey was approved by the University of Iowa Institutional Review Board (IRB) prior to administration. Recruitment was completed using the University of Iowa mass email service. A sign advertising the study was also used. The trials were completed by 50 males, without facial hair or respiratory illnesses whom were between the ages of 18-35 at the time of the study. Participants were students at the University of Iowa. This demographic is often naïve to wearing a respirator and does not have preconceptions about comfort associated with each brand or the cost differences between N95 FFR models. Limiting participation to males was intended to reduce facial shape variation allowing one-size-fits-all respirators to be purchased. However, face size was measured using a GPM model 106 caliper (Zurich, Switzerland). Specifically, the bizygomatic
breadth (facial width near cheek bones) was measured using the calipers. Although there are many facial measures that can be used in anthropometry research, the selected measure is commonly associated with respirator fit.\(^{(39)}\)

Most trials were conducted in the University of Iowa College of Public Health, with the remainder conducted at the Engineering building and Iowa Memorial Union. When a participant arrived, general information about the study and associated risks were explained. They were then given the survey and told to try on each N95 FFR for two minutes each. A random number generator was used to assign the order in which the six N95 FFRs were worn for each participant. The N95 FFRs were randomly assigned a number 1-6 to prevent the participants from gaining any additional information. Participants were allowed to fill in the survey during or after the two-minute period. Participants waited several seconds before preceding to the next N95 FFR. The evaluation of the N95 FFRs was relative to one another. Therefore, the participants could change their answers between N95 FFRs as they observe differences in comfort between masks. Participants were asked to draw a single line through the answer they want to change and circle their final answer. After all the N95 FFRs were finished being evaluated, the participants were given five minutes to try on the N95 FFRs again in any order.

**Statistical Methods**

Microsoft Excel was used to characterize the material property data. Graphs and tables were created to display the physical properties of each N95 FFR. Regression analysis was performed by setting the intercept to zero and recording the slope value for pressure drop versus flow rate for each FFR.
The survey data were considered non-parametric. Therefore, the Kruskal-Wallis test was applied using MiniTab version 18 statistical software. The non-parametric Dunn’s test was used to determine if the median survey scores for each question are statistically different between each FFR type. Spearman’s rank correlation coefficient was calculated to compare the association between N95 FFR physical properties and participant responses. An alpha value of 0.05 was considered significant. The qualitative survey responses for question four were coded numerically to allow statistical tests to be performed. Fit was coded as one, temperature as two, and ease of breathing three.

**Results**

Differences in pressure drop were observed between the ten N95 FFRs. Figure 1 and Figure 2 show the differences in pressure drop across the four applied flow rates (0.6 LPM, 1.6 LPM, 2.6 LPM, 3.6 LPM) filter only and all layers trials. Overall, a positive linear relationship was observed between flow rate and pressure drop. Both graphs show that the Dentec AD4N95 and Honeywell N95FFR had the greatest pressure drop, while the RZ mask and Moldex 4200 had the least. Pressure drop values ranged from 4.55-12.77 mm H₂O at 3.6 LPM flow rate. Figure 3 (filter only) and Figure 4 (all layers) show the effect of surface area corrections on pressure drop. A positive linear relationship was observed between pressure and flow rate. Table 1 shows the percent change in pressure drop between the all layers and filter only trials for each mask type with surface area corrections applied. The largest percent change was 39.16% for the 3M Aura 9210+, while the smallest change of 5.93% was for the Moldex 2200. After the correction, the Moldex 4200 had the lowest pressure drops and the Honeywell N95 FFR had the highest pressure drops across the applied flow rates. The slope values for each N95 FFR can be
seen in Table 2. Slope values were greater for the regressions using all mask layers compared to that of the filter only regressions. This trend was present across all N95 FFR types.

Table 3 provides the averages of solidity, total weight, surface area, pressure drop, and water vapor transmission across the ten N95 FFR types. Solidity ranged from 0.02 (Dentec AD2N95) and 0.07 (Moldex 2200). Water vapor transmission varied from 0.22 g (3m 8511, exhalation valve not included) to 0.38 g (Moldex 4200). The smallest surface area excluding the RZ Mask, was 174.71 cm² (3M 8210) and the largest was 313.87 (Moldex 4200). Pressure drops at 3.6 LPM ranged between 4.55 mm H₂O (Moldex 4200) and 12.77 mm H₂O (Dentec AD4N95).

Figure 5 graphically shows the average scores for question one, two, and three across the six N95 FFRs evaluated in the qualitative portion of the study that used a 1 – 6 Likert scale. Overall, the Honeywell 4200 had the highest total score across the first three survey question (Table 4). The 3M 8210 had the lowest score across the first three questions.

For question four, the qualitative responses were coded as one, two, and three for data analysis (Table 5). Figure 6 shows the distribution of responses (choice 1,2,3) for question four with respect to N95 FFR type. Response one (fit against face) was the most common response for all N95 FFR types except for the 3M 8511, which had response two (temperature) as the highest scored category. Figure 7 shows the cumulative count by response choice for question four. Response one (fit) was selected the most often followed by response two (temperature), and three (ease of breathing). On average,
question four was able to predict the lowest scoring of the three prior questions (Table 4), with the exception of the 3M Aura 9210+.

Also notable is the observation that the Honeywell 4200 had the lowest count for internal temperature for question four. This count was the lowest received for any of the N95 FFRs (Figure 6). This N95 FFR also had the highest comfort score out of any of the other N95 FFRs for temperature (Table 4). This relationship was expected as the N95 FFR with the lowest score for “importance in terms of discomfort” also had the highest average score regarding comfort for the same parameter (temperature).

A comparison of two 3M brand N95 FFRs is displayed in Figure 8. The 3M 8511 has an exhalation valve and the 3M 8210 does not have an exhalation valve. For question four, the participants found that fit was more important in terms of discomfort for the 3M 8210. Likewise, results obtained from the study involving measurements of internal temperature (Table 6) shows a 0.59 °C lower temperature in the 3M 8511 compared to the 3M 8210. However, the largest difference between the two masks was between the average scores for question one (fit). The average scores for questions one, two, and three were both greater for the 3M 8511 (Table 4).

The Kruskal-Wallis test was performed for questions one (fit), two (temperature), and three (ease of breathing). The results from these tests demonstrated that there was a significant difference between the median levels of mask scores for each of these questions (p < 0.001). Table 7, Table 8, and Table 9 show the results of the post-hoc Dunn’s test with respect to questions one, two, and three. Each table shows which N95 FFRs are statistically different from one another, where FFRs not sharing the same letter are different. No statistically significant differences were observed with respect to fit.
scores except for the 3M 8210, which was only similar to the Moldex 2200 (Table 7).

Only the Honeywell 4200 had a score that was statistically different from the other N95 FFRs with respect to temperature (Table 8). The 3M 8210 was the only mask that was statistically different with respect to ease of breathing (Table 9).

The Spearman coefficient between pressure drop (3.6 LPM) and ease of breathing score was 0.2 (p=0.7), and 0.6 (p=0.2) for water vapor transmission and temperature score.

Descriptive statistics regarding facial measurements can be found in Table 10. The mean bizygomatic breadth measurement was 15.65 (cm).

**Discussion**

This study included a comparison of FFRs with a wide variety of material properties. For questions one, two and three (fit, temperature, ease of breathing) the Honeywell 4200 N95 FFR had the highest scores, while the 3M 8210 had the lowest scores across all questions. However, receiving a high score from participants was not related to a measurable mask property. Mask properties were not strongly associated with the responses that participants gave for temperature and ease of breathing. For example, the Spearman’s correlation coefficient between pressure drop and ease of breathing score was 0.2, and 0.6 for water vapor transmission and temperature. Additionally, neither value was statistically significant. Fit was found to be the most important in terms of discomfort followed by temperature and ease of breathing. Fit was rated as the most important in terms of discomfort as there were only small differences between other mask properties (e.g., water vapor transmission, temperature). Fit could be assessed almost immediately during the short trial times. Roberge et al. (2013) suggests that pressure drop
between low pressure drop masks can be difficult for participants to discern.\textsuperscript{(32)}

Participants reported ease of breathing as less important in terms of discomfort than fit in question four. The results of the valve (3M 8511) versus no-valve (3M 8210) temperature test suggests that, at low activity levels, the small difference in temperature is likely indiscernible. Between the 3M 8511 and 8210 the largest difference in scores was for fit. The temperatures between the remaining masks were likely indistinguishable to the wearer.

Pressure drop measurements in the laboratory can be compared to the ease of breathing that participants experienced. Ease of breathing was rated as least important in terms of discomfort. Roberge et al. 2013 gave participants three cup-shaped FFRs that only differed in terms of pressure drop values, which were 3 mm, 6 mm, 9 mm H\textsubscript{2}O. \textsuperscript{(32)} They also found no statistically significant differences in the influences that the masks had on subjective ratings, physiological parameters, or pulmonary function variables. Under this view, participants cannot detect small differences in pressure drop, therefore the ease of breathing score should have been more similar between FFRs. However, their study is limited by its small sample size and use of only cup-shaped FFRs. Kim et al. 2015 suggested that pressure drop values below 9 mm H\textsubscript{2}O may not result in additional physiological or subjective benefits. Physiological variables were not measured in this study so it is uncertain whether the ten N95 FFRs would differ in the affect that they have on these variables. The Moldex 4200 had the lowest pressure drop measurements. The Moldex 4200 also had the second highest overall score of 4.52. 4.52 was the best score for traditional cup-shaped N95 FFRs for ease of breathing.
A low-pressure drop was anticipated to correlate with a high score for ease of breathing. However, the Spearman’s correlation coefficient between pressure drop and ease of breathing was low and not statistically significant. The Moldex 4200 N95 FFR is the only one with “AirWave” which is a pattern of repeated folds. This design also has the largest surface area which may contribute to the low pressure drop and increased airflow through the mask. Participants reported the highest scores for ease of breathing in this mask compared to 3M 8511 which has an exhalation valve. It is uncertain if the participants could accurately discern this difference in ease of breathing. The 3M 9210+ was the only fold flat mask in this study. It had the second lowest pressure drop measurement and the third highest score of 4.22 for ease of breathing.

The Honeywell 4200 had the highest pressure drop across flow rates when corrected for surface area. However, it the highest average score for ease of breathing. This suggests that participants may not be able to accurately discern the pressure drop of the N95 FFRs. The Honeywell 4200 is considered by the manufacture to be an elastomeric half mask respirator. However, it uses disposable N95 filter media very similar to a traditional cup-shaped N95 FFR. Its exhalation valve may have contributed to its high ease of breathing score. However, the 3M 8511 also had an exhalation valve and was ranked third in terms of ease of breathing. The 3M 8511 scored better than the Moldex 2200 and 3M 8210, only slightly below the 3M Aura. If the N95 FFRs were worn for a longer duration and at a higher work intensity then the exhalation valve may have had more of an effect on temperature. The 3M 8210 had the third highest pressure drop measurement (of six FFRs) and the lowest overall score for ease of breathing. Overall, participants had a difficult time distinguishing the ease of breathing for each
mask. This difficulty is indicated as all of the N95 FFRs were statistically similar except for the 3M 8210. It is unclear why this may have been rated the lowest in this category as this is not supported by pressure drop or water vapor transmission data.

Percent change values, calculated from all layers and filter-only pressure drop trials revealed differences in the N95 FFR construction has on pressure drop. Moldex N95 FFRs have the smallest percent change between these trials. This finding is likely due to the plastic webbing material that is used for support on the outside (thick webbing) and in between layers (thin webbing). Therefore, the filter layer alone comprises most of the FFR. 3M, Moldex, and Dentec take a different approach to designing respirators using a rigid non-woven structural layer(s). Slope values were lower for the filter-only layers which was expected. Solidity did not vary much between the FFRs. Total weights ended up being of no use relative to the questions selected to evaluate comfort.

Respirator fit against the face also varied by the type of N95 FFR. Fit was considered to be most important in terms of discomfort by the participants. The Honeywell 4200 elastomeric half mask type N95 FFR had the highest score for fit against the face of 4.36. This data suggests that the elastomeric casing was found to be more comfortable to the participants. However, the Honeywell 4200 fit score was not statistically higher than four of the five other masks. The Honeywell 4200 was also the heaviest respirator, this did not influence participants’ perceptions, which in part may be due to the short use duration. Participants complained about the FFR straps pulling hair, particularly when the 3M 8210 was worn. Participants also noted that the 3M 8210 fit awkwardly or felt smaller compared to the other N95 FFRs. The surface area of the 3M 8210 does not suggest that it is much smaller the other N95 FFRs. The 3M 8210 had the
lowest score for question one (fit against face) and was statistically different from 4 of the other 5 masks (Table 7). The Honeywell 4200 had a different mechanism to secure it to the user’s head. One of the straps had a semi-rigid piece that sits on the crown of the head, the second piece goes below the ears and connects to the first piece with a clasping mechanism made of two plastic hooks. One hypothesis could be that the elastomeric facepiece distributes facial pressure in a way that is perceived as comfortable. The area contacting the face is flexible and soft compared to the rigid edges of the cup shaped N95 FFRs. However, all of the masks were statistically similar except for the 8210, which is similar to the Moldex 2200. This suggests that distinguishing differences in fit was difficult for participants.

The Honeywell 4200, and both Moldex masks do not use a nose bar. The area around the nose is often sensitive to discomfort. Nose bars can apply pressure which may increase resistance when breathing. However, the 3M 8511 N95 FFR score was almost identical to the Honeywell 4200 in terms of fit. The 3M 8511 also scored better than both of the Moldex N95 FFRs in this category. Without controlling for additional variables, we cannot determine the relationship between nose bar presence and comfort. Several participants commented that the Moldex N95 FFRs fit awkwardly on the top of their nose near the center of the eyebrows. However, this observation was not consistent among all of the participants. This could be related to facial dimensions, size, and shape. The 3M 9210+ was the only fold flat mask evaluated by participants. Prior studies have suggested that the fold flat design may decrease seal pressure, improving facial comfort.\(^{16}\) It is difficult to discern how much of an impact this design had on fit. However, it did score better than three N95 FFRs, and the top three scores did not differ by very much.
Participants found temperature to be the second most important factor in terms of discomfort. The Honeywell 4200 had the highest score for temperature followed by the Moldex 4200. The 3M 8511 only scored better than the 3M 8210. Based on this evaluation the participants could not distinguish the effects of exhalation valve. Use duration and sedentary activity level may be responsible for this. In a laboratory setting the 3M 8511 was 0.59 °C cooler than the 3M 8210. It is unlikely that this temperature difference could be perceived by participants under the test conditions. The difference in ratings for temperature between these N95 FFRs was not statistically significant based on results of the Dunn’s test. Literature has suggested that exhalation valves can reduce discomfort and exertion compared to FFRs with no exhalation valve.\(^{(28)}\) The Honeywell 4200 with the highest temperature score also had the highest water vapor transmission. However, water vapor transmission and surface area were not a good predictor of temperature score across mask types. This was demonstrated by the small and statistically insignificant Spearman’s correlation coefficient \([0.6]\). The Honeywell 4200 was the only mask that was statistically different from all other N95 FFR types for temperature.

The intent of question four was to determine which of the first three questions was most important in terms of discomfort. This response was expected to be the same as the previous question with the lowest score. With the exception of the 3M Aura, question four was able to predict the previous question that had the lowest average score for each N95 FFR. The lowest response count (temperature) in question four was able to predict the highest overall comfort score in the study, which was the question two (temperature) for the Honeywell 4200. This result should have been expected as question four is describing which property was most important in terms of discomfort. Question four was
able to predict the lowest category ranking for all but one N95 FFR. However, the value of question four appears limited when comparing across N95 FFRs. Each N95 FFR has a total count of 50 for question four between the three choices, in contrast the use of a Likert scale allows the extent of the difference in parameter to be compared between N95 FFRs.

One study reported a mean bizygomatic breadth of 14.35 cm for men.\(^{(39)}\) However, the mean bizygomatic breadth in this study (Table 10) was in the 95 percentile of the results in the larger study. Most of the values were close to the mean although several outliers are responsible for the large range of 7.4 cm.

Future research can compare the physiological impacts of different N95 FFRs on workers across several activity levels. Collaboration with an employer may allow for N95 FFRs to be tested in a real working environment. This collaboration could result in the collection of more detailed qualitative data. As respirators continue to be developed with new features; the use of quantitative and qualitative tests can assure employers that the FFR will be acceptable to their workers. Providing workers with several options of N95 FFRs may be the best solution to match the preferences of a diverse workforce. Multiple N95 FFR options should be a consideration as fit testing is required by OSHA and a worker may not be able to pass a fit test for each N95 FFR. The availability of different sizes may also be a consideration in purchasing N95 FFRs.

**Limitations**

The results in this study are representative only of the conditions in which they were tested. This study was conducted indoors, with N95 FFRs worn only for a short two minute period of time, with a sedentary activity level. Therefore, conditions including
activity level and ambient conditions may vary based on the work environment. New conditions have the potential to change worker perceptions. Although the pressure drop through each N95 FFR did vary, it is difficult to discern how much of an impact this had on comfort. The sensitivity of the voltage power source may have resulted in random error. The output was not completely consistent, which may have resulted in inaccuracies in pressure measures. Moldex 2200 and 2300 appeared to be similar except for the absence of an exhalation valve in the Moldex 2200. If the material is identical than this would illustrate variability in the pressure measurements. However, running three trials helped to account for the variability between measurements.

Quantitative and qualitative respirator fit testing was not performed in this study. It is possible that the participants’ evaluation of comfort was influenced by the quality of the seal it had on the user. Therefore, if the respirator did not physically fit the user properly and provided compromised protection, then this may have allowed increased airflow into the FFR. Fit testing would ensure that workers evaluated the comfort of FFRs that they would be allowed to wear in an actual workplace.

Moldex N95 FFRs use a plastic webbing material for support. These layers cannot be compressed and therefore had to be removed to prevent air from leaking in the pressure apparatus. Although this material has holes to allow air to pass through, there is the potential for the values in Figure 6 and Figure 8 (all layer trial) to be represented with a lower pressure drop than if it was measured using another method. Trials using RZ Mask F2 filter did not include the neoprene casing, only the filter media cartridge. Therefore, this mask may be represented more favorably (lower pressure drop) than its actual pressure drop value. The RZ Mask is not N95 approved by NIOSH. This FFR was
not used in water vapor transmission testing as it could not be cut to fit the sampling apparatus.

Water vapor transmission testing was not conducted by a third-party laboratory. Although ASTM E96 was used as the basis for determining water vapor transmission, using a lab that specializes in this service (automated equipment) would increase the accuracy of the results. The Honeywell 4200 was the only elastomeric style N95 FFR, this major difference could have contributed to it receiving the highest scores for the participant trials. Additionally, the qualitative survey results rely on the assumption that participants were able to accurately distinguish between the N95 FFRs and gave honest opinions. Many of the scores in Table 4 are similar and it is possible that there no discernable difference for a particular property. Psychological factors may have influenced the perceptions of the participants. For example, if the mask fit poorly they may have been inclined to give low scores for other questions. Lastly, although the results for each question are statistically significant overall, only one FFR at most could be statistically differentiated within a single question.

**Conclusion**

The purpose of this study was to evaluate the physical properties of N95 FFRs that are related to comfort. The N95 FFRs varied in pressure drop, water vapor transmission, surface area, and design features. Associations were evaluated between the physical properties measured in a laboratory setting and perceived comfort of participants wearing the N95 FFR. The elastomeric Honeywell 4200 N95 FFR was given the highest scores across all three questions (fit, temperature, ease of breathing) by participants and the 3M 8210 was given the lowest scores across questions. However, the median scores
were not necessarily statistically significant between all FFRs within a question type. Therefore, participant ratings were not consistent with the material property results. Spearman’s correlation coefficients for ease of breathing score and pressure drop, and temperature score and water vapor transmission were small and insignificant.

In terms of discomfort, fit was considered the most important followed by temperature, and ease of breathing. Since the N95 FFRs were worn for a short period of time it makes sense that ease of breathing may have been rated as least important, followed by temperature. This is supported by research that suggests that low pressure drop respirators cause indistinguishable differences in physiological variables.\(^{(32)}\) There is also a threshold in which people can detect difference. Inactivity may have made it difficult for participants to discern temperature differences between trials. The largest difference between two 3M N95 FFRs with and without an exhalation valve was fit. Temperature only differed slightly in the comparison trial. A preference for fit is reasonable as the short trial times capture the initial face feel of the FFR. The participants’ preferences may be the same over a longer period of time, or their preferences may change. However, if the fit is uncomfortable during the initial trial then it is unlikely that this will change over a longer period of time. Providing workers with several options of N95 FFRs may be the best solution to match the preferences of a diverse workforce. This should be a consideration as fit testing is required by OSHA and a worker may not be able to pass a fit test for each N95 FFR. The availability of different sizes may also be a consideration in purchasing N95 FFRs.
Figure 1. Average pressure drop measurements from the separated filter layer of ten different N95 FFR types performed at four different flow rates.
Figure 2. Average pressure drop measurements from samples containing all filter media layers of ten different N95 FFRs at four different flow rates.
Figure 3. Average pressure drop measurements from the separated filter layer of ten different N95 FFR types performed at four different flow rates. Flow rate values were corrected for differences in surface area between the N95 FFRs.
Figure 4. Average pressure drop measurements from samples containing all filter media layers of ten different N95 FFR types at four different flow rates. Flow rate drop values were corrected for differences in surface area between the N95 FFRs.
Table 1. Percent of total pressure drop contributed to by the filter layer.

<table>
<thead>
<tr>
<th>Brand</th>
<th>% of total pressure drop</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M 8210</td>
<td>70.28</td>
</tr>
<tr>
<td>3M 8511</td>
<td>68.06</td>
</tr>
<tr>
<td>Dentec AD2N95A</td>
<td>76.17</td>
</tr>
<tr>
<td>Dentec AD4N95</td>
<td>88.32</td>
</tr>
<tr>
<td>RZ Mask- F2 filter *</td>
<td>68.53</td>
</tr>
<tr>
<td>Moldex 2300</td>
<td>92.39</td>
</tr>
<tr>
<td>Moldex 2200</td>
<td>94.07</td>
</tr>
<tr>
<td>Honeywell 4200</td>
<td>80.90</td>
</tr>
<tr>
<td>3M Aura 9210+</td>
<td>60.84</td>
</tr>
<tr>
<td>Moldex 4200</td>
<td>93.99</td>
</tr>
</tbody>
</table>

* Non-N95
Table 2. The slope values* are listed for the unadjusted pressure drop measurements for the all layers and the separated filter layer.

<table>
<thead>
<tr>
<th>Brand</th>
<th>All layers</th>
<th>Filter only</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M 8210</td>
<td>2.62</td>
<td>1.84</td>
</tr>
<tr>
<td>3M 8511</td>
<td>2.08</td>
<td>1.42</td>
</tr>
<tr>
<td>Dentec AD2N95A</td>
<td>2.46</td>
<td>1.86</td>
</tr>
<tr>
<td>Dentec AD4N95</td>
<td>3.54</td>
<td>3.13</td>
</tr>
<tr>
<td>RZ Mask- F2 filter</td>
<td>1.36</td>
<td>0.93</td>
</tr>
<tr>
<td>Moldex 2300</td>
<td>2.94</td>
<td>2.73</td>
</tr>
<tr>
<td>Moldex 2200</td>
<td>2.56</td>
<td>2.39</td>
</tr>
<tr>
<td>Honeywell 4200</td>
<td>3.51</td>
<td>2.84</td>
</tr>
<tr>
<td>3M Aura 9210+</td>
<td>2.84</td>
<td>1.72</td>
</tr>
<tr>
<td>Moldex 4200</td>
<td>1.25</td>
<td>1.17</td>
</tr>
</tbody>
</table>

* Pressure drop (mm H2O) relative to change in flow rate (LPM)
Table 3. Solidity, total weight, surface area, pressure drop, and water vapor transmission of ten N95 FFR types.

<table>
<thead>
<tr>
<th>Brand</th>
<th>Water vapor transmission (g)</th>
<th>Surface Area (cm²)</th>
<th>Total weight (g)</th>
<th>Pressure drop at 3.6 LPM (mm H₂O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M 8210</td>
<td>0.24</td>
<td>174.71</td>
<td>9.79</td>
<td>9.63</td>
</tr>
<tr>
<td>3M 8511</td>
<td>0.22</td>
<td>181.82</td>
<td>14.39</td>
<td>7.44</td>
</tr>
<tr>
<td>Dentec AD2N95A</td>
<td>0.31</td>
<td>180.35</td>
<td>10.46</td>
<td>9.01</td>
</tr>
<tr>
<td>Dentec AD4N95</td>
<td>0.28</td>
<td>209.42</td>
<td>10.25</td>
<td>12.77</td>
</tr>
<tr>
<td>RZ Mask- F2 filter</td>
<td>-</td>
<td>134.95</td>
<td>46.55</td>
<td>4.93</td>
</tr>
<tr>
<td>Moldex 2300</td>
<td>0.33</td>
<td>177.13</td>
<td>22.12</td>
<td>10.54</td>
</tr>
<tr>
<td>Moldex 2200</td>
<td>0.32</td>
<td>187.84</td>
<td>16.7</td>
<td>9.27</td>
</tr>
<tr>
<td>Honeywell 4200</td>
<td>0.38</td>
<td>159.39</td>
<td>109.41</td>
<td>12.66</td>
</tr>
<tr>
<td>3M Aura 9210+</td>
<td>0.23</td>
<td>214.37</td>
<td>9.47</td>
<td>10.33</td>
</tr>
<tr>
<td>Moldex 4200</td>
<td>0.26</td>
<td>313.87</td>
<td>14.78</td>
<td>4.55</td>
</tr>
</tbody>
</table>
Figure 5. Distribution of survey responses for questions one, two, and three across six different N95 FFRs.
Table 4. Average and total scores for survey questions one, two, and three across six N95 FFR types.

<table>
<thead>
<tr>
<th>Mask</th>
<th>Brand</th>
<th>Question 1 (fit)</th>
<th>Question 2 (temperature)</th>
<th>Question 3 (ease of breathing)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Moldex 2200</td>
<td>3.50</td>
<td>3.90</td>
<td>4.02</td>
<td>11.42</td>
</tr>
<tr>
<td>2</td>
<td>Honeywell 4200</td>
<td>4.36</td>
<td>5.24</td>
<td>4.66</td>
<td>14.26</td>
</tr>
<tr>
<td>3</td>
<td>3M 8210</td>
<td>3.16</td>
<td>3.66</td>
<td>3.94</td>
<td>10.76</td>
</tr>
<tr>
<td>4</td>
<td>3M 8511</td>
<td>4.34</td>
<td>3.74</td>
<td>4.16</td>
<td>12.24</td>
</tr>
<tr>
<td>5</td>
<td>3M Aura 9210+</td>
<td>4.28</td>
<td>3.92</td>
<td>4.22</td>
<td>12.42</td>
</tr>
<tr>
<td>6</td>
<td>Moldex 4200</td>
<td>4.04</td>
<td>4.12</td>
<td>4.52</td>
<td>12.68</td>
</tr>
</tbody>
</table>
Table 5. Question four qualitative responses were coded as numbers for data analysis.

<table>
<thead>
<tr>
<th>Question #</th>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fit against face</td>
</tr>
<tr>
<td>2</td>
<td>Temperature inside mask</td>
</tr>
<tr>
<td>3</td>
<td>Ease of breathing</td>
</tr>
</tbody>
</table>
Figure 6. Question four responses separated by question and N95 FFR numbers.
Figure 7. Cumulative count of responses for question four separated by responses choice.
Figure 8. Comparison of survey responses between N95 3M 8210 (no exhalation valve) and 3M 8511 (exhalation valve).
Table 6. Effect of exhalation valve on internal FFR temperature.

<table>
<thead>
<tr>
<th></th>
<th>Temperature (°C)</th>
<th>Difference (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M 8210 (no exhalation valve)</td>
<td>27.86</td>
<td>0.59</td>
</tr>
<tr>
<td>3M 8511 (exhalation valve)</td>
<td>27.27</td>
<td></td>
</tr>
</tbody>
</table>
Table 7. Dunn’s test of question one (fit) responses across six different N95 FFRs, and median scores.

<table>
<thead>
<tr>
<th>Mask</th>
<th>Comparison</th>
<th>MEDIAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moldex 2200 -1</td>
<td>AB</td>
<td>3</td>
</tr>
<tr>
<td>Honeywell 4200 - 2</td>
<td>A</td>
<td>5</td>
</tr>
<tr>
<td>3M 8210 - 3</td>
<td>B</td>
<td>3</td>
</tr>
<tr>
<td>3M 8511 - 4</td>
<td>A</td>
<td>4</td>
</tr>
<tr>
<td>3M Aura 9210+ - 5</td>
<td>A</td>
<td>5</td>
</tr>
<tr>
<td>Moldex 4200 - 6</td>
<td>A</td>
<td>4</td>
</tr>
</tbody>
</table>
Table 8. Dunn’s test of question two (temperature) responses across six different N95 FFRs, and median scores.

<table>
<thead>
<tr>
<th>Mask</th>
<th>Comparison</th>
<th>MEDIAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moldex 2200 - 1</td>
<td>B</td>
<td>4</td>
</tr>
<tr>
<td>Honeywell 4200 - 2</td>
<td>A</td>
<td>6</td>
</tr>
<tr>
<td>3M 8210 - 3</td>
<td>B</td>
<td>4</td>
</tr>
<tr>
<td>3M 8511 - 4</td>
<td>B</td>
<td>4</td>
</tr>
<tr>
<td>3M Aura 9210+ - 5</td>
<td>B</td>
<td>4</td>
</tr>
<tr>
<td>Moldex 4200 - 6</td>
<td>B</td>
<td>4</td>
</tr>
</tbody>
</table>
Table 9. Dunn’s test of question three (ease of breathing) responses across six different N95 FFRs, and median scores.

<table>
<thead>
<tr>
<th>Mask</th>
<th>Comparison</th>
<th>MEDIAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moldex 2200 -1</td>
<td>BC</td>
<td>4</td>
</tr>
<tr>
<td>Honeywell 4200 - 2</td>
<td>AB</td>
<td>5</td>
</tr>
<tr>
<td>3M 8210 - 3</td>
<td>C</td>
<td>4</td>
</tr>
<tr>
<td>3M 8511 - 4</td>
<td>BC</td>
<td>4</td>
</tr>
<tr>
<td>3M Aura 9210+ - 5</td>
<td>ABC</td>
<td>4</td>
</tr>
<tr>
<td>Moldex 4200 - 6</td>
<td>AB</td>
<td>5</td>
</tr>
</tbody>
</table>
Table 10. Participant facial measurements.

<table>
<thead>
<tr>
<th></th>
<th>Bizygomatic breadth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>15.65</td>
</tr>
<tr>
<td>SD</td>
<td>1.36</td>
</tr>
<tr>
<td>Min</td>
<td>10.20</td>
</tr>
<tr>
<td>Max</td>
<td>17.60</td>
</tr>
<tr>
<td>Range</td>
<td>7.40</td>
</tr>
<tr>
<td>Median</td>
<td>15.78</td>
</tr>
</tbody>
</table>
CHAPTER III: CONCLUSION

The purpose of this study was to evaluate the physical properties of N95 FFRs and their influence on user comfort. This pilot project has allowed me to better understand the research process. I was able to critically review literature and contribute to the field of industrial hygiene. I enjoyed participating in the creation of the study design. During the study design process, statistical methods should be a consideration in the development of survey questions and the use of the resulting data. I was able to improve my ability to work with numerous deadlines and a finite budget. I gained experience working with regulations and approval processes while communicating with the IRB office. This experience will help me when working with regulatory agencies in the future. I will be better prepared to plan in anticipation of delays and deadlines in my career. For example, IRB approval and changes take several months of dialog to complete. This pushed back my start date for conducting human trials. I learned how to write a grant proposal and secure research funding. This funding could not be used until IRB approval was completed, resulting in several weeks with a limited number of N95 FFRs for trials in the laboratory. Ordering, tracking, and distributing supplies should be an early consideration in the research process. It was initially challenging to recruit the 50 participants for this study. I spent many hours sitting at a booth unsuccessfully trying to recruit participants. I then used the mass email service provided through the university and was able to secure enough participants within 48 hours. The compensation that was provided in combination with the mass email service allowed me to attract a large candidate pool. Recruitment should be considered early in the research process. This project has helped me to improve my organizational skills while working with numerous manuals, spreadsheets, and word
documents. I gained a better appreciation for the use of continuous and discrete measurements data. It is important to understand how your equipment works. Understanding that pressure sensors work by producing an electrical output in response to a physical phenomenon helped in calibration and troubleshooting. I enjoyed this opportunity to add to the knowledge regarding N95 FFR properties and comfort. My intent for this study is to help employers select N95 FFRs that are best suited for their workplace environment. Overall, this project has helped me to improve my organization, planning, goal setting, and task management skills. Future studies can evaluate N95 FFR comfort in a variety of environments and have workers perform tasks that will emphasize differences in N95 FFR designs and material properties. The relationship between new features and comfort should be evaluated.
APPENDIX: SUPPLEMENTAL INFORMATION FOR CHAPTER II
Figure A1. FFR brands and models.
N95 Facemask Trials:

Participants will try on each of the 6 facemasks for 2 minutes, with a 30 second break between consecutive facemasks. Participants will then have up to 5 minutes to try on the facemasks again (in any order) and finish filling out the evaluation form.

The categories below will be used to evaluate facemask comfort. A scale of 1-6 is used. A rating of 6 indicates most comfortable/least uncomfortable, where a rating of 1 indicates the least comfortable/most uncomfortable. Circle the number that best matches your perception of the mask.

<table>
<thead>
<tr>
<th>Participant #</th>
<th>Mask #</th>
<th>Fit against your face:</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Uncomfortable</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Comfortable</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Temperature inside mask:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncomfortable</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comfortable</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ease of breathing:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncomfortable</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comfortable</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Of the three qualities (fit, temperature, and ease of breathing), which do you consider to be the most important in terms of discomfort? (Circle your response)

Fit against your face  Temperature inside mask  Ease of breathing

Figure A2. Page one of survey given to participants.
Figure A3. Box plot display of question one (fit) data of 50 participant responses.
Figure A4. Boxplot display of question two (temperature) data across 50 participant responses.
Figure A5. Boxplot display of question three data (ease of breathing) of 50 participant responses.
Figure A6. Temperature versus time for 3M 8511 trial one.
Figure A7. Temperature versus time for 3M 8511 trial two.
Figure A8. Temperature versus time for 3M 8210 trial one.
Figure A9. Temperature versus time for 3M 8210 trial two.
REFERENCES