



**OCCUPATIONAL NOISE DOSE REDUCTION VIA BEHAVIOR
MODIFICATION USING IN-EAR DOSIMETRY AMONG USAF PERSONNEL
EXPOSED TO CONTINUOUS AND IMPULSE NOISE**

THESIS

Jesse A. Trawick, Captain, USAF

AFIT-ENV-18-M-240

**DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY**

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

DISTRIBUTION STATEMENT A:
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the United States Air Force, the Department of Defense, or the United States Government.

This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

AFIT-ENV-18-M-240

OCCUPATIONAL NOISE DOSE REDUCTION VIA BEHAVIOR MODIFICATION
USING IN-EAR DOSIMETRY AMONG USAF PERSONNEL EXPOSED TO
CONTINUOUS AND IMPULSE NOISE

THESIS

Presented to the Faculty
Department of Systems and Engineering Management
Graduate School of Engineering and Management
Air Force Institute of Technology
Air University
Air Education and Training Command
in Partial Fulfillment of the Requirements for the
Degree of Master of Science in Engineering Management

Jesse A. Trawick, B.S.E.E.

Captain, USAF

March 2018

DISTRIBUTION STATEMENT A:
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

AFIT-ENV-18-M-240

OCCUPATIONAL NOISE DOSE REDUCTION VIA BEHAVIOR MODIFICATION
USING IN-EAR DOSIMETRY AMONG USAF PERSONNEL EXPOSED TO
CONTINUOUS AND IMPULSE NOISE

Jesse A. Trawick, B.S.E.E.
Captain, USAF

Approved:

Jeremy M. Slagley, PhD (Chairman)

Date

Lt Col Robert Eninger, PhD (Member)

Date

John Elshaw, PhD (Member)

Date

Lt Col Andrew Hoisington, PhD (Member)

Date

Abstract

The purpose of this research was to investigate the use of in-ear noise dosimetry and worker feedback to reduce noise exposures among combat arms instructors and heavy equipment operators in the Air Force. Specifically, this thesis sought to determine how effectively hearing protection devices (HPDs) are being utilized currently, and whether providing at-ear noise exposure data to workers results in reduced noise exposures or changes in worker attitude. These questions were addressed by performing a six-month field study using dosimeters to record worker noise exposures under HPDs. Subjects served as their own control, receiving feedback in only the latter half of the study. Nineteen subjects volunteered for the study, with both continuous and impact noise represented. The collected noise exposure data was examined for differences between the control and feedback phases that could indicate more effective HPD use using ANOVA analysis. Additionally, a 7-point Likert survey was utilized to examine worker attitude towards HPDs and hearing health, and worker medical histories were examined for evidence of previous noise injuries.

This research effort found a significant reduction in noise dose rate (-2.5 dB at $p = .019$) for continuous noise exposed workers following introduction of periodic noise exposure feedback on in-ear noise levels under hearing protection. This effect was not detected at the individual level due to limited samples. No effect was detected in impulse noise-exposed subjects, primarily due to limitations in dosimeter technology and its response to impulse noise. No correlation was found between subjects affective and cognitive attitude components and noise dose rates. Additionally, while subjects reported positive impressions of the in-ear dosimeter and noise exposure feedback, few reported using the immediate feedback functions to control noise exposure levels within a work shift.

Acknowledgements

I would like to extend my sincerest gratitude to my thesis advisor, Dr. Jeremy Slagley, for his support and guidance throughout this thesis effort. His insight and up-beat encouragement were greatly appreciated. Additionally, I would like to thank Lt Col Robert Eninger, Captain Bill Murphy, Andrew Wells, SSgt Adam Whiteman, Austin Szekacs, Dr. Elizabeth McKenna and Major Daniel Williams for their technical guidance. Lastly, this research would not have been possible without the support and enthusiasm of the men and women of the 88th Civil Engineer Squadron, the 88th Security Forces Squadron, and the 445th Security Forces Squadron.

Jesse A. Trawick

Table of Contents

	Page
Abstract	iv
Acknowledgements	v
Table of Contents	vi
List of Figures	ix
List of Tables	xi
List of Symbols	xii
List of Acronyms	xiv
 I. Introduction	 1
1.1 Background	1
1.2 Problem Statement	1
1.3 Research Questions	4
1.4 Methodology	4
1.5 Assumptions and Limitations	5
1.5.1 Non-Interference with Subject's Duties	6
1.5.2 Expected Noise Exposure Data	6
1.5.3 Expected Combat Arms Noise Sources and Levels	7
1.5.4 Expected Pavements and Grounds Maintenance Noise Sources and Levels	8
1.5.5 Limited Choice of In-Ear Dosimetry Equipment	8
 II. Literature Review	 9
2.1 Health Impacts, Prevalence, and Risk Factors for Noise Induced Hearing Loss	9
2.1.1 Prevalence of Occupational Noise Induced Hearing Loss	10
2.1.1.1 Among Military	10
2.1.1.2 Among Construction Workers	11
2.1.2 Risk Factors for Noise Induced Hearing Loss	13
2.1.2.1 Physical Characteristics	13
2.1.2.2 Impulse Noise	13

	Page
2.1.2.3 Ototoxic Chemicals	17
2.2 Fundamentals of Hearing Conservation Programs	18
2.3 Hearing Protective Device Effectiveness	19
2.3.1 Laboratory Methods for Determining Attenuation	20
2.3.1.1 Real Ear Attenuation at Threshold	20
2.3.1.2 Microphone in Real Ear	21
2.3.1.3 Acoustical Test Fixture	21
2.3.2 Limitations of Hearing Protective Device Use in the Field	22
2.3.2.1 Estimating Field Attenuation using Laboratory Data	22
2.4 Worker Motivation and Hearing Protection Device Use	23
2.4.1 Health Belief/Promotion Model	23
2.4.2 Theory of Planned Behavior Model	26
2.4.3 Tripartite Theory of Attitudes	28
2.5 Noise Exposure Feedback in Hearing Conservation Programs	30
2.5.1 Field Usage of MIRE Dosimeters with Continuous Feedback	30
III. Methodology	33
3.1 Equipment	33
3.1.1 Dosimeters	33
3.1.1.1 Equipment and Software Errors and Malfunctions	35
3.1.2 Hearing Protection Devices	37
3.1.3 Acoustic Calibrator	40
3.1.3.1 Larson Davis CAL200	40
3.1.3.2 G.R.A.S. Pistonphone Type 42AP	41
3.1.4 Additional Microphone and Probes	41
3.1.4.1 67SB Blast Probe Microphone	41
3.1.4.2 GRAS 45CB Acoustic Test Fixture	42
3.2 Laboratory Impact Noise Analysis	42
3.3 Field Study	44
3.3.1 Recruitment and Personal Attenuation Rating Testing	44
3.3.1.1 Selection and Recruitment of Volunteers	45
3.3.1.2 Personal Attenuation Rating Testing	45
3.3.2 Control Phase	47
3.3.3 Feedback Phase	48
3.4 Participant Questionnaire	49
3.4.1 Creation of the Health Behavior Questions	49
3.4.2 Testing Construct Validity	50
3.4.3 Testing Construct Reliability	50
3.5 Data Analysis	51
3.5.1 Laboratory Study Data Analysis	51
3.5.1.1 Processing the Data for Analysis	51

	Page
3.5.1.2 Comparison of Impulse Noise Metric Means for Laboratory Data	52
3.5.2 Field Study Data Analysis	53
3.5.3 Analysis of Worker Attitude and Noise Dose Rate	55
3.5.3.1 1-Way ANOVA Analysis of Attitude Constructs versus Phase	55
3.5.3.2 Testing Attitude Moderation of Feedback-Performance Relationship	56
IV. Results and Discussion	58
4.1 Participant Demographics and Attrition	58
4.1.1 Demographics	58
4.1.2 Subject Medical History	60
4.1.3 Personal Attenuation Rating Test Results	61
4.1.4 Subject Attrition	62
4.2 Calibration Data Analysis	63
4.3 QuietDose Microphone Performance under Lab Conditions	65
4.4 Field Study Analysis Results	69
4.4.1 1-Way ANOVA by Subject	69
4.4.1.1 Continuous Noise Group	69
4.4.1.2 Impulse Noise Group	69
4.4.1.3 Full Factorial ANOVA - Continuous Noise Group	72
4.4.1.4 Full Factorial ANOVA - Impulse Noise Group	74
4.5 Worker Attitude Analysis	75
4.5.1 Moderation of Affect, Cognition and ACC on HPD Performance	77
4.6 QuietDose Usability	80
4.7 Discussion	81
V. Conclusions	84
Appendix A: Calibration and Data Download Protocols	85
Appendix B: Participant Survey Questions	92
Appendix C: MATLAB Source Code	96
Bibliography	103

List of Figures

Figure	Page
1.1 Dosimeter microphone placement and the process of assessing NIHL risk [83] .	3
1.2 M2 Browning	7
1.3 M240 Machine Gun	7
1.4 Typical Riding Mower	8
1.5 Typical Airfield Sweeper	8
2.1 Measurement of A-Duration [21]	16
2.2 Health Belief Model [1]	24
2.3 Theory of Planned Behavior [2]	27
3.1 In-The-Ear QuietDose Dosimeter Kit Contents	34
3.2 F-MIRE Earplugs for QuietDose Dosimeter	38
3.3 Impact Sport Earmuff	39
3.4 Peltor LiteCom Plus Earmuff	39
3.5 Larson Davis Acoustic Calibrator	40
3.6 G.R.A.S. Pistonphone Calibrator with Blast Probe Adapter	41
3.7 Acoustic Test Fixture	42
3.8 Impulse Noise Generator	42
3.9 Lab Testing Conditions	43
3.10 Subject Performing PAR Testing During Recruitment	46
3.11 Example Noise Report	49
3.12 Moderation of ACC on Feedback-HPD Performance Relationship	56
3.13 Moderation of Affect/Cognition on Feedback-HPD Performance Relationship .	56
4.1 Subject Demographics	59
4.2 Subject Duty Information	59

Figure	Page
4.3 Subject External Noise Exposures	60
4.4 Reported Medical History	61
4.5 Subject PAR Testing Results	62
4.6 Microphone Configurations	65
4.7 Typical A-Weighted Waveform	66
4.8 QuietDose Microphone Interference from Impulse Bypassing Earmuffs	67
4.9 Effects Plot - Leq_{hr} By Subject	73
4.10 Effects Plot - Leq_{hr} By Phase	73
4.11 Overall QuietDose Usability Score	81
A.1 Add/Associate User Screen	85
A.2 Set Date and Time Screen	87
A.3 Device Calibration Screen	88
A.4 Calibration History Screen	89
A.5 CoolTerm Connection Options	91
A.6 Raw Data Example in CoolTerm Software	91

List of Tables

Table	Page
3.1 QuietDose Earplug Attenuation Ratings in Decibels (Mean/Standard Deviation)	38
3.2 Earmuff Attenuation Ratings in Decibels (Mean/Standard Deviation) [3, 39]	39
3.3 Results of Measure Reliability Tests - Affect and Cognition	51
3.4 Summary of Impulse Noise Metrics and Assumptions	53
4.1 Calibration Analysis Results	64
4.2 2-Sample T-test for Microphone Performance Results	68
4.3 1-Way ANOVA Analysis Results - Continuous Noise Group Blocked by Subject	70
4.4 1-Way ANOVA Analysis Results - Impulse Noise Group Blocked by Subject .	71
4.5 Full Factorial ANOVA and Effects Test - Continuous Group	72
4.6 Ordered Differences Report - Continuous Noise Group	73
4.7 Full Factorial ANOVA and Effects Test - Impulse Group	75
4.8 1-Way ANOVA - Continuous Group - Affect, Cognition, & ACC vs Survey . .	76
4.9 1-Way ANOVA - Impulse Group - Affect, Cognition, & ACC vs Survey	76
4.10 Full Factorial ANOVA - Continuous Group - Noise Dose vs Phase & Attitude .	78
4.11 Full Factorial ANOVA - Impulse Group - Noise Dose vs Phase & Attitude . . .	79
4.12 QuietDose Usability Survey Response Summary	80

List of Symbols

Symbol	Definition
$\alpha_{A,T}$	A-weighting coefficient
$\alpha_{C,T}$	C-weighting coefficient
AW(t)	A-weighting Filter
β	Correction Factor (constant), 0.01
CW(t)	C-weighting Filter
$\%D_{85,3}$	Noise Dose Percent, AF/NIOSH Standard
$\%D_{hr}$	Noise Dose Rate in Percent per Hour
$\%D_{1000rounds}$	Noise Dose Rate in Percent per 1000 rounds
dB	Decibels, No weighting
dBA	Decibels, A-weighting
dB C	Decibels, C-weighting
Hz	Hertz
K_T	Kurtosis
$L_{Aeq,8hr}$	Sound Level Equivalent, A-weighting
$L_{Aeq,100ms}$	Sound Level Equivalent, 100 milisecond intervals
$L_{F_{eq}}$	Sound Level Equivalent, F-Weighting
L_{hr}	Noise Dose Rate in Decibels per Hour

Symbol	Definition
$L_{1000rounds}$	Noise Dose Rate in Decibels per 1000 Rounds
N	Number of Impulses
O_T	Oscillation Coefficient
P(t)	Sound Pressure Level, No-weighting
p_A	A-weighted Sound Pressure Level (Pascals)
p_F	F-weighted Sound Pressure Level (Pascals)
p_0	Reference Sound Pressure Level, $2 * 10^{-5}$ Pascals
T	Exposure Time
T_{8hr}	Equivalent Time in Seconds, 28,800 s

List of Acronyms

Acronym	Definition
ACC	Affective Cognitive Consistency
AFI	Air Force Instruction
AFPD	Air Force Policy Directive
AHAAH	auditory hazard assessment algorithm for the human
ANSI	American National Standards Institute
ATF	Acoustic Test Fixture
CDC	Centers for Disease Control
DOD	Department of Defense
DOERHS	Defense Occupational and Environmental Health Readiness System
EPA	Environmental Protection Agency
F-MIRE	Field Microphone In Real Ear
GUI	Graphical User Interface
HBM	Health Belief Model
HPM	Health Promotion Model
HCP	Hearing Conservation Program
HPD	Hearing Protective Device
IRB	Institutional Review Board
MIRE	Microphone In Real Ear
NIHL	Noise Induced Hearing Loss
NIOSH	National Institute for Occupational Safety and Health
NRR	Noise Reduction Rating
OEL	Occupational Exposure Limit
OSHA	Occupational Safety and Health Administration

Acronym	Definition
PAR	Personal Attenuation Rating
PTS	Permanent Threshold Shift
REAT	Real Ear Attenuation at Threshold
STS	Standard Threshold Shift
TPB	Theory of Planned Behavior
TRA	Theory of Reasoned Action
TTS	Temporary Threshold Shift
TWA	Time-Weighted Average

OCCUPATIONAL NOISE DOSE REDUCTION VIA BEHAVIOR MODIFICATION USING IN-EAR DOSIMETRY AMONG USAF PERSONNEL EXPOSED TO CONTINUOUS AND IMPULSE NOISE

I. Introduction

1.1 Background

Occupational safety and health is a subject of great importance to the Air Force, with numerous policy documents dedicated to the reduction of job-related injury or illness for its personnel. Foremost among these documents is Air Force Policy Directive (AFPD) 48-1, which highlights the need to “optimiz[e] the safety and health of AF personnel” through the use of appropriate surveillance, prevention, and control programs [31]. For noise related hazards, Air Force Instruction (AFI) 48-127 and MIL-STD-1474E provide the roles, responsibilities and procedures for implementation of the Air Force’s occupational noise and hearing conservation program [5, 21]. Specifically, these policy documents establish the governing Occupational Exposure Limit (OEL), provide guidance for calculation of the Time-Weighted Average (TWA) dose, dictate the procedures for performing noise hazard assessments and selection of Hearing Protective Device (HPD), and prescribe methods for performing medical evaluations for Noise Induced Hearing Loss (NIHL) [5, 21].

1.2 Problem Statement

While AFI 48-127 establishes a comprehensive approach to occupational noise exposure risk assessment and mitigation, it does note several limitations that reduce the effectiveness of the program in preventing NIHL [5]. First, the attenuation provided by HPDs varies between workers even when worn appropriately. The instruction does provide

a calculation for at-ear noise levels under earplugs or muffs using the Noise Reduction Rating (NRR) and ambient noise levels; however, the actual noise attenuation provided by HPDs will vary based on numerous factors, including personal fit and worker proficiency using HPDs. Second, the actual noise attenuation provided by HPDs is limited by the presence of noise pathways to the inner ear via vibration through bone. Lastly, the current methods of using NRRs to calculate at-ear noise levels are designed to protect 98% of workers when HPDs are used appropriately [5]. A portion of the population that is more susceptible to NIHL may still incur injury under this program, especially if that individual is less adept at wearing earplugs appropriately.

Despite the occupational noise and hearing conservation program's best efforts to prevent noise-related injuries, permanent NIHL and tinnitus are still a significant contributor to overall disability numbers among Department of Defense (DOD) personnel. In 2014, the Department of Veteran's Affairs reported over 2.3 million auditory disabilities among veterans; making it the second most prevalent category of disability among veterans and accounting for 13% of all compensated disabilities [90]. In the Air Force specifically, a survey of audiometric testing results from 2005 to 2011 discovered that 8.3% of all personnel had permanent hearing loss [85], known as a Permanent Threshold Shift (PTS). This survey also uncovered higher than expected rates of hearing loss among career fields that are not routinely exposed to high levels of noise and are thus not required to participate in the Air Force Hearing Conservation Program (HCP).

The overall prevalence of noise-related injuries among Air Force personnel could be attributed to the limitations of using NRRs to estimate at-ear noise levels; however, the Air Force does not currently have an established procedure for performing measurement of at-ear noise levels directly. The lack of at-ear noise level data makes it difficult to determine how effective HPDs are at mitigating noise exposures among DOD personnel or what excess health risk is associated with improper HPD use. Additionally, for

impulse noise, the auditory risk models recommended by AFI 48-127 and MIL-STD-1474E have been recently been shown to contradict each other, providing recommended allowable exposures numbers that differ drastically [59]. Due to equipment and resource limitations, calculations of these allowable exposures often require blanket assumptions that may underestimate the risk of hearing damage for small arms gunfire or complex noise, consisting of both impulse and continuous noise sources [59, 83]. Given the current inaccuracies of the models for impulse and complex noise and conflicting auditory risk approximations, there has been increased interest in at-ear dosimetry due to measuring at the eardrum. This measurement location bypasses the need for assumptions and correction factors for microphone placement, potentially providing a more accurate representation of auditory risk of hearing loss, as depicted in Figure 1.1 [83].

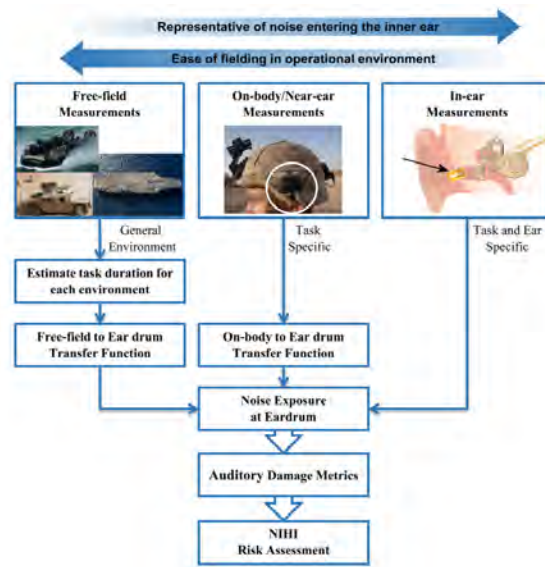


Figure 1.1: Dosimeter microphone placement and the process of assessing NIHL risk [83]

Figure reused in its original form under Creative Commons License.

DOI: <https://doi.org/10.1016/j.heares.2016.11.008>

1.3 Research Questions

The focus of this thesis effort was on evaluating how effectively HPDs are being used to control exposures to noise among Combat Arms and Grounds Maintenance personnel, as well as determining if utilizing feedback on exposure levels under hearing protection results in reduced exposures over time or improvements in individual attitude towards hearing protection. Thus, this thesis effort will address the following questions:

1. How effectively are HPDs being utilized in the field among Air Force personnel?
2. Does providing at-ear noise exposure feedback result in reduced noise exposures over time?
3. Do noise exposure changes over time correlate with worker attitude regarding HPD use?

By answering these questions, this research effort sought to evaluate if the current hearing conservation program in the Air Force is effective at controlling noise exposures and if at-ear noise exposure feedback is a worthwhile addition to improve overall hearing health in the Air Force. Due to small sample size and other measurement errors, it was not possible to conclusively meet this goal. However, this research effort provided valuable insight into noise exposures and hearing protection use for a subset of the Air Force's workforce, as well as determined usability of the QuietDose dosimeter system as part of the Air Force's HCP.

1.4 Methodology

This research effort uses recently developed methods utilizing daily at-ear noise dose data collection, continuous worker feedback and intervention programs to lower noise dose over time, similar to those of recent studies. In 2011, Yale researchers examined daily at-ear noise level data collected by Alcoa, an industrial manufacturing company, over the

course of six years [53]. They found that use of continuous at-ear exposure monitoring combined with intervention for overexposures resulted in significant reductions in NIHL among workers for Alcoa. This method was replicated at three additional manufacturing facilities in May of 2011, with a total of 66 active participants [52]. Overall, it was determined that the use of daily feedback resulted in reduction of exposures that exceeded 85 dBA (8-hour TWA). Additionally, it found that “[o]f individuals who consistently used the device, 89% believed it helped them control their noise exposure and 96% say it helped them preserve their hearing.” While these initial studies do indicate significant success with using a continuous monitoring and intervention program utilizing daily at-ear noise level data, these programs have not been evaluated in occupational settings other than manufacturing or in batch processes where noise levels are more variable.

This thesis effort sought to utilize the same product and method for collection of at-ear noise exposure data as the above studies. The study included Air Force Combat Arms and Grounds Maintenance personnel and lasted for a period of approximately 6 months. Collected noise exposure data was provided to the individual on a regular schedule and any significant increases or decreases in at-ear noise levels were noted. Additionally, each individual’s motivation regarding HPD use was evaluated using a 7-point Likert scale survey at key points during the study. This data was analyzed for significant changes as the study progressed and evaluated for correlations with at-ear noise exposures.

1.5 Assumptions and Limitations

While every effort was made to control or measure all factors that may influence the results of this thesis effort, due to resource limitations or procedural necessity certain assumptions and limitations had to be made during the course of this study. This section lists these factors, the assumptions made, and discusses the implications for the end results.

1.5.1 Non-Interference with Subject's Duties.

During the field study portion of this thesis, subjects were asked to wear dosimetry devices in place of their normal HPDs. However, any further interference was directly avoided. There was no incentive provided for use of the QuietDose dosimeter, nor was the data collected provided to supervisors for correction of potential safety deficiencies. This limitation was a necessity of the research protocol, which protects the subject from personal identification, retribution for participation in the study, or non-conformance with safety protocol. This factor likely contributed to lack of volunteers, but ultimately created a more accurate representation of the expected results in the wider population, as subjects were not forced or led to perform behaviors they otherwise would not have.

Additionally, subjects were not asked to perform their duties differently than normally performed or asked to impose administrative controls (such as limiting exposure time) based on the provided noise exposure reports. This limitation not only reduced the researchers influence on the results, but lessened the impact on the duty performance of the subjects. In order to protect the individual and ensure continued mission completion, this limitation was paramount to the conduct of this study.

1.5.2 Expected Noise Exposure Data.

Due to limited researcher manpower resources, high likelihood of intermittent noise exposures of widely varying intensity, and the difficulty associated with measuring impact noise in the field, it was prohibitively time-intensive to perform an extensive noise characterization of the exposures experienced during this field study. Instead, previous noise characterization surveys performed by on-base personnel as part of the shop's HCP were used to provide a reference point for the expected noise exposures. These baselines, as well as the typical noise sources assumed for each group, are detailed below. Additionally, in order to account for daily differences in the noise source and isolate the impacts of

worker behavior, the noise dose data collected was weighted by shift duration or number of impulses, as appropriate.

1.5.3 Expected Combat Arms Noise Sources and Levels.

According to the shop HCP, the Combat Arms instructors participating in this study are expected to be exposed to a TWA sound level of 115 dBA in an average 8-hour day while on the indoor range. The typical noise sources experienced are M9 pistols and M4 semi-automatic rifles, with typical peak sound levels of approximately 157 dB at the shooter's position [40]. However, it should be noted that the instructors were observing students, not firing themselves. Therefore, their exposure could differ significantly from that of the shooter position with decreased proximity to the students. These differences were not observed or reported. All training occurs at an indoor range on Wright-Patterson AFB, therefore noise reflection is expected. There was one exceptional exposure encountered during this study, where the instructors gave training on M2 Browning 0.50 caliber machine gun (Figure 1.2), M240/249 machine guns (Figure 1.3), and the M82 Barrett 0.50 caliber rifle. Expected peak noise levels at the gunner position for these weapons are 153-160 dB for the machine guns [40] and around 150 dB for the M82 rifle. This training session was performed in free field conditions at Fort Knox in Kentucky.



Figure 1.2: M2 Browning



Figure 1.3: M240 Machine Gun

1.5.4 Expected Pavements and Grounds Maintenance Noise Sources and Levels.

The pavements and grounds maintenance personnel participating in this study, according to their shop HCP, are expected to be exposed to intermittent noise with a TWA of approximately 90 dBA. Typical noise sources consist of machinery and equipment, such as riding lawn mowers and airfield sweepers as shown in Figure 1.4 and 1.5. This equipment is expected to produce noise at around 90 dBA continuously at the operator's position while running.



Figure 1.4: Typical Riding Mower



Figure 1.5: Typical Airfield Sweeper

1.5.5 Limited Choice of In-Ear Dosimetry Equipment.

The in-ear dosimetry equipment utilized during the course of this thesis effort was provided directly from the manufacturer. Ten of the provided units were purchased and the other nine were provided on loan. The provided model, QuietDose Exposure Smart Protector Personal Dosimeter (Honeywell Safety Products USA, Smithfield, RI), is currently a discontinued product and not available for commercial purchase. Other commercial options were available from the same manufacturer, but they were too cost-prohibitive to conduct a study of this size and length. The manufacturer made no attempt to influence the results of this study in any way as a condition of providing the equipment.

II. Literature Review

2.1 Health Impacts, Prevalence, and Risk Factors for Noise Induced Hearing Loss

Excessive noise exposures have been linked to numerous adverse health outcomes, both auditory and non-auditory, and shown to impact a person's quality of life and mental health [14]. In addition to NIHL, a worker may lose the ability to achieve absolute silence in the absence of detectable noise, a condition called tinnitus. Tinnitus is a persistent buzzing, clicking, or ringing in the ears that affects as many as 36 million Americans. Consistent exposure to high levels of noise has also been linked to increased blood pressure and stress levels, hypertension, and fatigue. Additionally, the presence of NIHL may make communication difficult, leading to miscommunication, loss of worker productivity, and workplace accidents. Persons affected by NIHL have also reported feelings of isolation and loss of intimacy with their partners as basic communication with loved ones becomes more difficult [14].

According to the American College of Occupational and Environmental Medicine, occupational NIHL is defined as “hearing loss that is a function of continuous or intermittent noise exposure and duration, and which usually develops slowly over several years [44],” or an increase in noise level required for detection, in the “noise sensitive” frequency regions of 3000 to 6000 Hz with recovery at around 8000 Hz. Threshold shifts can either be permanent (PTS) or temporary (Temporary Threshold Shift (TTS)), and their exact frequency location varies based on the source noise and the size of the subject's ear canals [44].

There is, however, no universal standard or procedure for defining and measuring threshold shifts. Occupational Safety and Health Administration (OSHA) CFR 1910.95 defines a Standard Threshold Shift (STS) as a “10 dB change from the baseline audiogram after age correction at 2000, 3000, and 4000 Hz [63]”. Additionally, CFR 1910.95 does

not require measurements at 8000 Hz. This makes it difficult to differentiate between occupational and age-related hearing loss, or presbycusis; which exhibits a similar threshold shift without the recovery at 8000 Hz. Coles, Lutman and Buffin suggest the use of a hearing threshold that is at least 10 dB greater at 3000, 4000, or 6000 Hz than the hearing threshold at 1000, 2000, and 8000 Hz [18]. Also, there is disagreement among studies on how the measurement is obtained. Some studies utilize the average loss in both ears, while others use the better or worse ear [48].

These discrepancies on how NIHL is defined and measured have significant impact on how prevalence of NIHL is reported, making comparison of studies difficult and often misleading. As such, no attempt to make direct comparisons between studies will be made. However, this thesis effort will use the OSHA standard as prescribed in AFI 48-127 to identify a TTS or PTS, which specifies a 10 dB average threshold shift at 2000 Hz, 3000 Hz, and 4000 Hz [5].

2.1.1 Prevalence of Occupational Noise Induced Hearing Loss.

In 2016, a comprehensive review of all relevant NIHL prevalence studies was completed by the National Institute of Occupational Health and the Norwegian Institute of Public Health [48]. Overall, they found that between 7% and 21% of hearing loss is attributed to occupational exposures, with the highest prevalence in developing countries. The occupations with the highest risk of NIHL are military, construction workers and agricultural workers [48]. Given this conclusion regarding occupational hearing loss risk, the population of interest for this thesis effort was military weapons instructors and Air Force construction workers. Further literature review to better understand the relative risk was limited to these populations and is detailed in the sections below.

2.1.1.1 Among Military.

The link between military service and NIHL is well-established in the research community, particularly for service members in careers with consistent gunfire or aircraft

noise exposures. The largest series of studies looked at incidence of hearing loss among over 140,000 infantrymen and found higher than expected NIHL rates when compared to unexposed populations [35–37]. Another longitudinal study followed soldiers deployed to Afghanistan and Iraq from 2003 to 2009 and found that reported cases of hearing loss increased significantly following combat action [38].

In the Air Force, a comprehensive study of audiometric testing results from 2005 to 2011 discovered that 8.3% of all Air Force personnel had NIHL [85], with higher than expected rates of hearing loss among career fields that are not routinely exposed to high levels of noise. However, the policy to report a PTS in the event of failure to perform a follow-up exam following detection of a TTS could explain a portion of this prevalence. After excluding reported PTS due to lack of follow-up exams, the prevalence of NIHL for all job categories was around 2.5%. Additionally, a noticeable increase in NIHL rates after the age of 35 was detected, which cannot be adequately explained by presbycusis [85].

The preponderance of the evidence available suggests that military populations, due to exposure to noise not commonly found in civilian populations, are subject to higher rates of NIHL. Therefore, military personnel, especially those with consistent exposure to gunfire noise, would be worthwhile to include in research on hearing conservation programs, hearing protection effectiveness, and preventative health behavior.

2.1.1.2 Among Construction Workers.

The vast majority of studies performed on construction workers relating to hearing loss are cross-sectional studies of a general population, and most are in agreement that construction workers experience higher than expected hearing loss versus non-exposed populations. One such study of Dutch construction workers found a median hearing loss of around 10-20 dB after correcting for age-related hearing loss [47]. Of particular importance, this study showed higher than expected losses for construction workers early in their career and for workers in noise levels typically considered low, between 80 and 88

dBA. A similar study of the general Norwegian population found that many construction trades experience a greater than 5 dB average threshold shift in the 3000, 4000, 6000 Hz range and are ranked among the top 31 occupations for hearing loss [24]. While cross-sectional studies are useful for measuring the overall effects of noise on occupational hearing loss and identifying areas of concern, they are not as useful as longitudinal studies in determining the rate at which hearing loss occurs for a given populace.

One of the only longitudinal studies of hearing loss among construction workers occurred over a period of 10 years, starting in the early 2000's and consisting of 8 separate tests for PTSs [79–81]. Over the first four years, the results indicated non-significant decreases in hearing ability [79], while at the end of the 10-year study an overall 10 dB increase was observed among participants [81]. One of the key differences for this series of studies versus other retrospective or cross-sectional studies is that the participants were construction apprentices early in their careers. Given that hearing loss is typically greatest during the first 5 years of exposure [44], this reduced but did not eliminate the bias towards slower hearing loss rates typical of more experienced populations. While not a direct comparison to this thesis effort, these studies highlight the necessity of interventions to prevent early hearing loss within the first 10 years of a career in construction, which is typical for military in construction duties. Additionally, while the longitudinal study focuses on building construction trades and this thesis focuses on pavement and grounds maintenance trades, the exposures are expected to be similar. The study's authors note that exposures occur intermittently with an expected range between 85 and 90 dBA [44], which is similar to the exposures characterized for the grounds maintenance participants in this field study.

2.1.2 Risk Factors for Noise Induced Hearing Loss.

2.1.2.1 Physical Characteristics.

Among the available literature, certain individual characteristics have been shown to correlate highly with NIHL. Understanding these effects can have a significant impact on the results of research on hearing loss, as a portion of the variance in hearing loss is likely attributable to factors discussed below.

Age is perhaps the most impactful and well supported factor, with older individuals being significantly more likely to develop hearing loss [48]. Much of this trend can be explained by presbycusis, thus it is important to correct for age according to OSHA 1910.95 Appendix F [63] when trying to determine if an occupational NIHL occurred. Gender has also been shown to correlate significantly with hearing loss, with men more likely to lose their hearing than women [48]. OSHA 1910.95 Appendix F provides different age correction factors for male and female to account for this difference [63]. Additionally, genetic background can play a large role in individual differences in susceptibility to hearing loss [48].

Socioeconomic factors, ethnicity, and certain illnesses have been shown to also contribute to NIHL, though evidence for these effects are much lower than age, gender, and genetics [48]. Nevertheless, low social class, education, and income increase the risk of NIHL slightly. Caucasians have a nominally higher risk of hearing loss than African Americans. Cardiovascular disease, hypertension, diabetes, and smoking could potentially contribute to increased risk, while ear disease has a moderately higher effect [48].

2.1.2.2 Impulse Noise.

According to the National Institute for Occupational Safety and Health (NIOSH), impulse noise is defined by "a sharp rise and rapid decay in sound levels and is less than 1 sec in duration [60]," and can be generated by an impact of one mass against another or a sudden release of force, such as an explosion or gunshot. While shorter in duration

than continuous noise, impulse noise has been shown in testing on chinchillas to have more damaging effects than continuous noise with equivalent energy [23, 34]. Additionally, the risk impulse noise poses can be hard to quantify due to most standard dosimetry equipment not requiring recording above 130 dB nor a response fast enough to adequately capture the impulse [42]. Given the increased risk and quantification difficulty, much work has been done to produce models that can accurately predict threshold shifts from a collection of a few representative impulse recordings. This work has resulted in development of four risk assessment standards: the $L_{Aeq,8hr}$, or 8-hour A-weighted sound level equivalent, the $L_{Aeq,100ms}$, or the sound level equivalent averaged over 100 millisecond intervals, the auditory hazard assessment algorithm for the human (AHAH) model [20, 21], and the kurtosis model [27, 88]. Each of these models has particular strengths and weaknesses in predicting hearing loss, which are discussed below.

The $L_{eq,8hr}$ metric is the oldest of the four models and is currently in use by several countries in Europe [21]. It involves finding the energy contained in an impulse after performing A-weighting, which filters the signal based on human response, and equates it to an equivalent 8 hour continuous noise signal of the same energy [58]. The $L_{Aeq,8hr}$ is calculated by Equation 2.1. While this model has incorporated some human ear assumptions, it overestimates risk for long duration impulses and underestimates risk for complex and high frequency noise [21, 83]. The assumptions of $L_{Aeq,8hr}$ also do not hold true above 140 dB, which is common for impulse noise [83].

$$L_{Aeq,8hr} = 10 \log \left(\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \frac{p_A^2(t)}{p_0^2} dt \right) + 10 \log \left(\frac{t_1 - t_2}{T_{8hr}} \right) + 10 \log(N) \quad (2.1)$$

In Equation 2.1, p_A is the A-weighted sound pressure level in Pascals, p_0 is the reference sound pressure for noise (2×10^{-5} Pascals), T_{8hr} is the 8-hr equivalent time in seconds (28,800 s), and N is the number of impulses in the recording.

An extension of the $L_{Aeq,8hr}$, the $L_{Aeq,100ms}$ performs a similar computation (See Equation 2.2) but limits the integration to only 100 millisecond intervals [83]. Like the $L_{Aeq,8hr}$, the $L_{Aeq,100ms}$ is an equivalent 100 millisecond exposure to continuous noise of the same energy. The $L_{Aeq,100ms}$ has included correction factors for impulses with varying A-durations that make up for the weaknesses of the $L_{Aeq,8hr}$. $L_{Aeq,100ms}$ can also be modified to include hearing protection ratings into the calculation [21]. However, the $L_{Aeq,100ms}$ is relatively new and has yet to receive substantial peer review [20, 21]. In the following equations, T is the length of the recording and A-duration is measured by finding the length of the peak in seconds (See Figure 2.1).

$$L_{Aeq,100ms} = 10 \log \left(\frac{1}{T} \int_0^T \frac{p_A^2(t)}{p_0^2} dt \right) \quad (2.2)$$

$$L_{Aeq,8hr} = L_{Aeq,100ms} - 54.6 - \begin{cases} 0 & A - duration \leq 0.2ms \\ 15 \log_{10} \left(\frac{A-duration}{0.2ms} \right) & 0.2ms < A - duration < 2.5ms \\ 16.4 & A - duration \geq 2.5ms \end{cases} \quad (2.3)$$

The AHAAH model involves the use of preprogrammed software or code to run a complex model of the human ear's response to an impulse waveform. Originally written in the now defunct Delphi language, it has since been exported to C++ and MATLAB to allow further development and research [20]. The AHAAH model was written to more accurately model the human ear and its reaction to impulse noise. However, some of the assumptions made in the model have been challenged by the American Institute

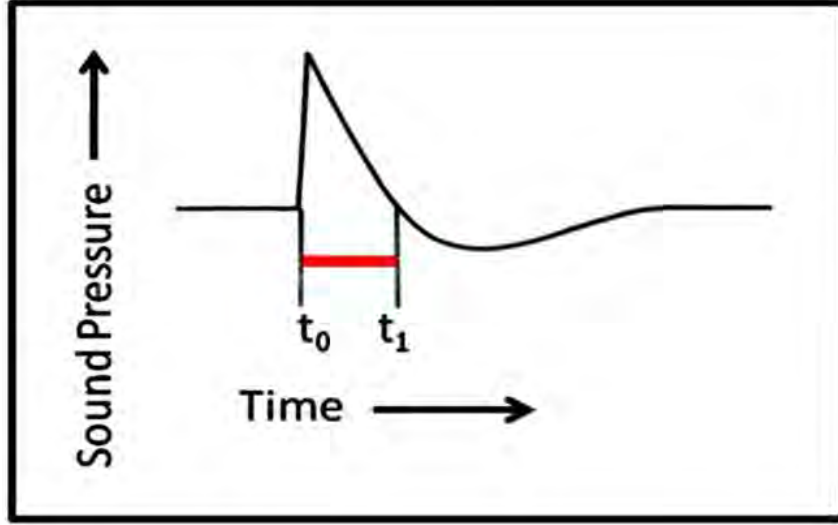


Figure 2.1: Measurement of A-Duration [21]

of Biological Sciences and are awaiting further review [21]. While the AHAH model has received validation through peer-review [15, 68, 69], a 2011 review of chinchilla data comparing the AHAH and $L_{Aeq,8hr}$ model found that $L_{Aeq,8hr}$ is a better predictor of threshold shifts [58]. Overall the reception of the AHAH model as a health hazard assessment tool appears to be positive [21], though most of the studies performed are by the U.S. Army Research Laboratory responsible for its development, which may introduce a bias.

The newest metric, kurtosis, takes advantage of two types of noise frequency weighting to better represent complex noise made up of continuous and impulse components [88]. This new weighting schema (called F-weighting), combines A-weighting, which describes continuous noise well, and C-weighting, which is better for impulse noise, using correction factors based on the the "peakedness" of the noise. The F-weighted noise signal has the basic form shown in Equation 2.4. The variables $\alpha_{A,T}$ and $\alpha_{C,T}$ are based on the kurtosis (K_T) and the oscillation coefficient (O_T) of the data, which describe how peaky the signal is compared to Gaussian noise. Once the F-weighted signal

has been calculated, the normal integration of the signal in Equation 2.7 can be used to determine the equivalent energy sound level, or L_{Feq} [88]. The kurtosis model has been shown to perform well as a risk criteria for animal studies [27, 88] and has shown promise as a correction factor for human PTS predictions [27]. However, due to the lack of complex noise in this study and the lack of peer review for the model currently, kurtosis will not be explored further for this thesis effort.

$$P_F = \alpha_{A,T}(AW(t) * P(t)) + \alpha_{C,T}(CW(t) * P(t)) \quad (2.4)$$

$$\alpha_{A,T} = \exp(\beta K_T O_T) \frac{1}{|\ln(O_T)| + 1} \quad (2.5)$$

$$\alpha_{C,T} = \exp(\beta K_T O_T) \frac{|\ln(O_T)|}{|\ln(O_T)| + 1} \quad (2.6)$$

$$L_{Feq} = 10 \log \left(\frac{1}{T} \int_0^T \frac{p_F^2(t)}{p_0^2} dt \right) \quad (2.7)$$

In Equations 2.4, $\alpha_{A,T}$ and $\alpha_{C,T}$ are weighting coefficients for the signal filters $[AW(t)$ and $CW(t)]$ calculated using Equations 2.5 and 2.6. $P(t)$ is the unweighted sound pressure signal in Pascals and P_F is the F-weighted signal in Pascals.

2.1.2.3 Ototoxic Chemicals.

Within the past 25 years, there has been much research on the connection between chemical exposures and NIHL [48]. In particular, organic solvents and heavy metals have been linked to increased hearing loss [76, 77]; sometimes the effects are additive [82] and sometimes synergistic [57].

During this research effort, all subjects are exposed to some level of organic solvents and the Combat Arms subjects are exposed to lead as part of their normal duties. However, this factor is expected to be present in equivalent amounts during both the control and

feedback phase; therefore, the effect of ototoxic chemicals on the results of this study should be negligible.

2.2 Fundamentals of Hearing Conservation Programs

A hearing conservation program is typically made up of five distinct activities: noise survey and data analysis, education and motivation, noise control, HPDs, and audiometric monitoring [87]. Each of these activities, working in concert with one another, is aimed at limitation or prevention of occupational hearing loss; however, there is disagreement with how to evaluate the effectiveness of these programs. The traditional method is to determine whether a program is complete, or that it has all required activities present in some manner. This method is considered regulatory, as OSHA regulations dictate that employers provide each of the listed activities when noise exposures exceed a TWA of 85 dBA as well as some guidelines for how to conduct some of the activities [63]. It does not prescribe, however, any metric to determine whether these elements are successful in prevention of occupational NIHL. Even when considered complete, a HCP will vary in effectiveness with the quality and rigor with which each of the activities is implemented. A program that meets regulatory standards may still encounter NIHL due to inaccuracies in noise exposure characterization, improper fitting and use of HPDs, calibration errors in measurement equipment, poor follow-up on audiometric testing, and insufficient education and motivation of the workforce [87].

Given the limitations of the traditional approach, there has been a push among hearing loss researchers to tie HCP effectiveness to worker health outcomes and the ability to prevent NIHL [87]. The most common method of doing so is to analyze trends in audiometric test results for a worker population, as detailed in the American National Standards Institute (ANSI) document *Evaluating the Effectiveness of Hearing Conservation Programs* [7]. This approach allows employers to identify deficiencies in their HCP early, before NIHL becomes too widespread [87]. However, this method

still requires that some hearing loss—permanent or temporary—occur first in order for deficiencies to be detected. Therefore, this method could still be improved upon or replaced with a method that identifies risk factors before NIHL presents itself.

Additionally, the use of a results-based metric allows researchers to analyze how effective certain HCP components are at preventing hearing loss. A recent review of biomedical articles relating to HCP effectiveness found that the average HCP did little to prevent PTS [89]. The only interventions studied that showed favorable results were those that used HPDs and those that provided more information on noise exposures to the worker as part of a comprehensive and well-implemented HCP. This review highlights the importance of having a HCP that is effective rather than just complete and the role that HPDs and worker motivation have on hearing loss rates.

Given the current state of research, any effort to improve an existing HCP, after establishing appropriate engineering and administrative controls to eliminate noise exposures where possible, should look to HPD use and worker motivation first to achieve the greatest effect on occupational NIHL rates. Additionally, providing worker feedback on real noise exposures shows promising results, though studies on HCPs that incorporate this are limited. These topics (HPDs, worker motivation, and noise exposure feedback) are explored in more depth in the following sections.

2.3 Hearing Protective Device Effectiveness

Given that many occupational noise exposures cannot be adequately mitigated using engineering or administrative controls, many companies must resort to using hearing protection as a last line of defense against NIHL in their workers, including the Air Force. Hearing protection use—or non-use—is often the most significant factor in predicting NIHL rates when supported by an effective HCP [89]. Given this trend, predicting hearing protection effectiveness when used appropriately has been a subject of much study. Several ANSI standards have been developed to test HPD attenuation for the purposes of

protecting the majority of individuals, with three recommended laboratory methods for determining noise attenuation: Real Ear Attenuation at Threshold (REAT), Microphone In Real Ear (MIRE), and Acoustic Test Fixture (ATF) [6, 8, 9], but only if worn in the same manner as in the laboratory by subjects representative of the actual population of users [13]. Several factors limit the effectiveness of applying laboratory data to field conditions, including worker training and motivation and bone vibration pathways. Each of these laboratory testing methods, the approximations used to predict real world attenuation, and the limitations of this data are discussed in the sections below.

2.3.1 Laboratory Methods for Determining Attenuation.

2.3.1.1 Real Ear Attenuation at Threshold.

The REAT method, detailed by ANSI S13.9 [6], for determining HPD attenuation is widely considered the “gold standard to which all other types of measurements are compared [13],” and is the basis for manufacturer NRR ratings as required by the Environmental Protection Agency (EPA) [25]. This testing method consists of determining the lowest sound level at several frequencies that is detectable by a series of subjects both with and without hearing protection, and taking the difference between those values to determine the subjects’ attenuation [13]. The mean attenuation for that HPD is then determined by calculating the attenuation obtained by about 50% of the subjects tested. This testing method has a particular strength: it accurately measures attenuation for a HPD regardless of sound level [12]. This greatly reduces the amount of testing required to accurately determine NRR.

This testing method has some acknowledged limitations, however [13]. First, it cannot be used to test hearing protectors with sound level dependent attenuation, such as active electronic or valve containing earplugs or muffs. This is due to the relatively low sound levels used during testing, which will not trigger these active methods of attenuating noise. Second, physiological noise can mask low frequency noise thresholds (under 500 Hz),

which elevates the reported value by a few decibels. Third, the experimenter is often heavily involved in the subjects' HPD fit, coaching them on use to obtain the maximum attenuation possible. This lack of realism has spurred ANSI to develop a second REAT testing method, called Method B or Subject Fit, in which the experimenter is prohibited from influencing the subjects' HPD fit [13]. This alternative method, described by ANSI S12.6, is designed to provide "an approximation of the upper limits that can be expected for groups of occupational users [9];" however, it has yet to replace Method A, or experimenter-supervised fit, as the standard by which manufacturers calculate NRR. Lastly, and most pertinent to this thesis effort, REAT testing methods have a tendency to underestimate protection levels for impulse noise [13]. Several studies have found that the actual attenuation for impulse noise is often equal to or larger than the attenuation level determined using continuous noise [13, 84]. Thus, when attempting to determine the actual attenuation for high-level impulse noise, it is important to use impulse noise as the testing standard.

2.3.1.2 Microphone in Real Ear.

MIRE testing is a measurement method in which the sound level is measured both under and outside HPDs and the difference is used to determine the attenuation [13]. While it has not replaced Method A testing for determining NRR, MIRE testing methods have a few distinct advantages over typical REAT methods. Namely, it is unaffected by low frequency masking, can be accomplished more quickly, and tends to have less variation in results. However, MIRE has its own measurement errors inherent for high level noise, due to bone conduction pathways limiting the effectiveness of the HPD [10].

2.3.1.3 Acoustical Test Fixture.

Similar to the MIRE testing method, the ATF testing method measures the sound level under and exterior to HPDs [13]. The key difference is that the human subject is replaced with a simulated headform and the microphone is built into the ear rather than

placing one into the ear canal of a live subject . This method allows experimenters to get measurements quickly, but is subject to all limitations of MIRE testing. Additionally, the use of a head-form in place of a live subject masks the effect of bone conduction, as current ATF technology does not accurately simulate the physical characteristics of the human skull [13].

2.3.2 Limitations of Hearing Protective Device Use in the Field.

When wearing HPDs, there are several pathways that limit the attenuation provided: air leaks, hearing protector vibration, structural transmission, and bone and tissue conduction. Each of these pathways provide an alternate route for noise exposures to enter the inner ear and potentially cause damage, even when hearing protectors are worn appropriately. Due to these factors and the relative difficulty conventional lab methods have with quantifying the associated risk these factor cause, several methods of correcting laboratory NRRs for field application have been developed, detailed below [13].

2.3.2.1 Estimating Field Attenuation using Laboratory Data.

Equations 2.8 through 2.10 are the primary calculations recommended to apply laboratory-derived NRRs to real-world conditions [13]. In each case, the exposure after the corrected NRR is applied should be less than the OEL chosen for that HCP. Equation 2.8 is a straight reduction of the NRR from the workplace noise level (L_{eq} , in dBC) and is only valid when the Subject Fit Method is used to derive the NRR. Equation 2.9 reduces the NRR by 7 dB to account for loss in accuracy when using A-weighted noise levels (L_{eq} , in dBA). Lastly, OSHA recommends derating the NRR an additional 50% for Method A data, as shown in Equation 2.10. The Air Force's HCP utilizes Equation 2.9 and Equation 2.10 for ANSI S12.6 and ANSI S3.19 derived data, respectively [5]. In Equations 2.8 to 2.10, L_{eq} is defined as the equivalent sound level of the workplace.

$$Exposure = L_{eq} - NRR_{SF} \quad (2.8)$$

$$Exposure = L_{eq} - NRR - 7dB \quad (2.9)$$

$$Exposure = L_{eq} - 0.5(NRR - 7dB) \quad (2.10)$$

2.4 Worker Motivation and Hearing Protection Device Use

The subject of motivation is one that has received significant attention—both inside of industrial hygiene and in general. How does one create an organizational culture that encourages individuals, with all their quirks and differences, to uniformly act in a way that may deviate from their natural inclinations? In the case of occupational safety, how does one get a worker to put their long-term health above more immediate concerns such as the job task, comfort, or speed? For occupational noise exposures that cannot be completely mitigated through engineering controls, the worker's motivation to protect themselves by using HPDs consistently and effectively is often the last line of defense against NIHL. Thus, it is imperative that an organization understand worker motivation and the factors that have the greatest impact on proper HPD use. This section explores two models commonly used to explain an individual's motivation regarding health behaviors: the Health Belief/Promotion Model and the Theory of Planned Behavior Model. Additionally, a more generalized attitude-behavior theory, the tripartite theory of attitudes, is explored.

2.4.1 Health Belief/Promotion Model.

The Health Belief Model (HBM) was developed by the US Public Health Service in the 1950's and has been widely used in both practice and research to this day [1]. In its conception, it was designed to explain why individuals fail to participate in disease prevention and detection programs. Rooted in expectancy-value theory, this theory hinges

on the belief that an individual that values an outcome will engage in behaviors they expect will attain that outcome. The HBM was originally designed to describe behaviors related to chronic disease, such as cancer or AIDS screenings [1], whereas the Health Promotion Model (HPM) has evolved to be used for behaviors that lead to higher quality of life, such as exercising and nutrition [66]. The differences between these two models is purely in their intended purpose, as they rely heavily on variations of the same constructs. Additionally, since hearing health can be either a chronic illness or a quality of life issue, depending on severity and an individual's perspective, both models could be applied interchangeably. Thus, for the purposes of this research effort, HBM and HPM will be treated as two facets of a single theoretical model.

Figure 2.2: Health Belief Model [1]

The HBM, shown in Figure 2.2, is highly dependent on six major constructs [1]:

1. Perceived Severity - Beliefs about the seriousness of the illness or injury
2. Perceived Susceptibility - Beliefs about the chances of being afflicted by an illness or injury
3. Perceived Benefits - Beliefs about an action's ability to prevent or control an illness or injury
4. Perceived Barriers - Beliefs about the costs of taking an action

5. Self-efficacy - Confidence in the ability to perform an action
6. Cues to Action - Situational triggers to perform an action

These constructs are indirectly influenced by demographics, as an individual's unique situation plays a large part in how they view the world [1]. In relation to overall health behavior research, this model has performed well in both prospective and retrospective studies; however, it has some distinct limitations. First, perceived benefits and barriers are the strongest predictors by far in longitudinal studies, with the length of time between construct measurements and the type of intervention acting as modifiers to all the constructs [17]. Second, the constructs appear to also modify each other under certain situations. For example, for conditions with low perceived severity and susceptibility, barriers and benefits become relatively unimportant [1]. Lastly, cues to action can vary widely in their implementation from reminders to policy and have yet to be defined adequately in research. As such, this element is often ignored entirely in research studies and has less substantiation than the other constructs.

Study of the HBM and HPM in relation to hearing health has typically been restricted to three general concepts: willingness to take a hearing test, willingness to obtain and use hearing aids, and HPD use. The first two concepts are unrelated to this research, as the Air Force HCP requires annual hearing tests regardless of an individual's willingness and is focused on prevention rather than treatment of hearing loss. The last concept, HPD use, is directly related, but is more limited in scope than this research effort. Most of the studies related to HPM are focused on HPD use versus non-use, with significant but very small effect sizes. This research effort inherently focuses only on a population that would be considered HPD users by these studies, given that the field study is purely voluntary and thus attracts only those interested in utilizing hearing protection regularly. Instead, this intervention is more interested in describing the characteristics of an individual that is more effective at using HPDs versus one that is going through the motions. Thus, one

would expect that the correlations between the HBM/HPM constructs and more effective HPD use be smaller or potentially non-existent, especially given the small sample size for this particular study.

This is not to say that the HBM/HPM model is inapplicable to this research effort, as it does provide insight on what factors to build into the treatment for the field study. Throughout all the studies performed using the HBM or HPM model to predict hearing protector use, the most significant factors have been perceived benefits, barriers, and self-efficacy [43, 49, 50, 65, 75]. As expected these are modified by an individual's demographics and interpersonal influences, which could be described as the safety culture of the surrounding social network [49, 75]. These findings are favorable for the selected treatment method in this research effort, as providing noise exposure feedback on in-ear levels allows the worker to directly see the benefits of using HPDs more effectively, empowering them to better protect themselves. Perceived barriers will be a challenge for this study, as the researchers have little control over how the individual shops run their overall HCP or the culture created within those shops.

2.4.2 Theory of Planned Behavior Model.

The Theory of Planned Behavior (TPB) Model is a derivative of the Theory of Reasoned Action (TRA) Model, which was developed by Martin Fishbein in 1967 to understand the correlations between attitudes, intentions, and behaviors [26]. This model has been well-tested in relation to health behavior, with multiple meta-analysis studies showing support for the relationship between its constructs and desired health behaviors [4, 22, 91]. Like the HBM, the TPB Model is grounded in expectancy-value theory, where an individual is likely to engage in behaviors that they expect will attain an outcome if they value that outcome [2]. The TPB model, shown in Figure 2.3, is defined by four major constructs:

1. Attitude - Personal beliefs about the behavior and behavioral outcome

2. Subjective Norm - Beliefs of others about the behavior and behavioral outcome and willingness to comply with those beliefs
3. Perceived Control - Beliefs about an individual's control over a behavior or behavioral outcome
4. Intention to perform the behavior - Modified by Attitude, Subjective Norm, and Perceived Control; Represents an individual's belief that they will perform a behavior

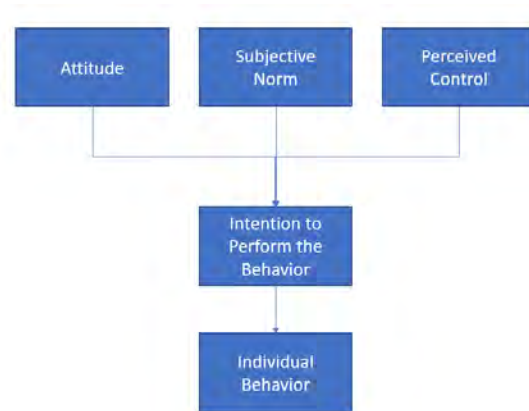


Figure 2.3: Theory of Planned Behavior [2]

Compared to HBM model, the TPB appears to measure many of the same variables, with Attitude representing Perceived Susceptibility, Severity, and Benefits; while Perceived Control measures Self-Efficacy. Like HBM, TPB constructs are moderated by demographics and an individual's culture, however, TPB attempts to isolate and measure some of those effects using the Subjective Norm measurement, which accounts for social pressures to perform an action or inaction [2]. Additionally, TPB is much more rigorously tested with better operationalization of all constructs, which increases its usefulness as a model for HPD use. Unfortunately, there has been little research in this area, with only one study performed by the Centers for Disease Control (CDC) showing significant correlations

between all the constructs and HPD use [71]. Like the studies for HBM, though, HPD use is defined by use or non-use and not varying degrees of performance.

In context of the field study for this research effort, the TPB still has some limitations. Due to the model's focus on describing whether an action will or will not take place, the constructs are likely to perform similarly if the measurement is changed to varying degrees of use rather than a binary measure. Additionally, the effect sizes in the CDC study are small when considering non-use versus use [71], therefore we can expect that any effects measured in this field study are likely to appear even smaller and could be masked by small sample sizes or calibration errors. While this model appears to be strong in predicting a behavioral outcome with lots of rigorous support, this thesis effort may be too small in scope to properly utilize it.

2.4.3 Tripartite Theory of Attitudes.

The attitude-behavior relation has long been a subject of much study in psychology, with the tripartite theory of attitudes being one of the oldest and most prominent areas of research. The tripartite theory of attitudes has history that dates back to the early 1960's, when it was first theorized that attitudes were made up of affective, cognitive and behavioral components [67]. The tripartite theory of attitudes has undergone several transformations since first conceived, however, the core concepts remain relatively constant. First, the affective component relates to an individual's beliefs and feelings towards an attitude object, while cognitive attitudes are rooted in thoughts and reasoning towards an attitude object [19, 54, 55, 67]. The behavioral component refers to responses and actions towards the attitude object [67]. Each of these components are considered separable and independently measurable, although they do have high correlation with one another [67].

In the prediction of behavior, the general consensus is that people seek to maintain consistency in affect, cognition, and behavior. This means that individuals that have high consistency in the affective and cognitive components of their attitude are more

likely behave in line with those components. This concept, called Affective Cognitive Consistency (ACC), has been studied extensively and received significant support [46, 55, 62]. However, when there is a mismatch in the affective and cognitive components, one component or the other takes precedence in predicting the behavior. Which construct better predicts behavior in the case of a mismatch appears to depend on the situation. Lavine, Thomsen, Zanna and Borgida found that affect is the primary predictor for low affective-cognitive consistency subjects in their study of attitudes towards presidential candidates [46]. Norman [62] and later Millar and Tesser [54], however, postulated that it depends on whether the behavior is cognitively-driven or affectively-driven. Cognitively-driven, or instrumental behaviors, are those that are done for a reason other than the behavior itself, whereas affectively-driven behaviors, or consummatory, are done because the behavior is rewarding [54, 67]. Further study of this effect found significant support for the moderating role of affective-cognitive consistency on the attitude-behavior relation, [55], which has been replicated in other applications [78].

In addition to the tripartite theory, it is important to note that it is possible for an individual to hold multiple—possibly conflicting—attitudes towards an object at once. This concept, called ambivalence, has received much support in the literature [16, 51, 67, 70]. Subjects with ambivalent attitudes may be subject to persuasion or context in determining which attitude presents itself [51, 70]. Another differing explanation for multiple attitudes and their presentation comes from dual-attitude theory, developed by Wilson, Lindsey and Schooler [92]. They hypothesize that attitudes are either automatic, or implicit, or must be activated by the individual, or explicit. Both implicit and explicit attitudes towards an object can be present at once, with the implicit attitude taking precedence until the individual is motivated to override it with an explicit attitude. As a general rule, implicit attitudes are more difficult to change, whereas explicit attitudes are changed easily [92].

The largest amount of application research in using the tripartite theory of attitudes is in effectiveness of behavioral persuasion using cognitively or affectively focused advertising [32, 41]. Studies of the job satisfaction-job performance relationship have also explored and found support for the moderating role of ACC in the attitude-behavior relationship [78]. There has, however, been no notable research concerning affective and cognitive attitudes and their relationship to occupational safety behavior. Given the current lack of occupational safety research utilizing the tripartite theory of attitudes, there is a need to further explore this area of research. Additionally, Of the models explored so far, the tripartite theory of attitudes holds the most promise for a study of this size. The primary constructs (affect and cognition) should present themselves strongly and provide enough nuance to be detected even in a small study group, unlike HBM or TPB. By ranking an individual's attitude relative to their peers, subjects can be stratified into tiers of more or less motivated individuals, which should correlate with HPD use effectiveness. In the case of a mismatch in ACC, either the cognitive or affective component should still be a predictor for HPD use.

2.5 Noise Exposure Feedback in Hearing Conservation Programs

2.5.1 Field Usage of MIRE Dosimeters with Continuous Feedback.

The largest effort to address the limitations of current methods of performing exposure assessments has been through a series of studies at Alcoa Incorporated, an aluminum manufacturing company operating across the United States. Prior to 2005, Alcoa utilized a HCP that exceeded the requirements dictated by OSHA, to include yearly fit tests for earplug-type HPDs and an action level of 82 dBA in an attempt to control worker noise exposures [53, 61]. Despite these efforts, threshold shifts continued to occur at an average rate of 1.7 dB per year [73].

In March of 2005, Alcoa incorporated daily exposure monitoring utilizing a Field Microphone In Real Ear (F-MIRE) dosimeter into their HCP at one of their factories in

Washington [53]. All workers who demonstrated a 5 dB PTS were required to utilize this equipment to continue employment. A group of Yale researchers conducted a retroactive analysis of audiometric data from 2000 to 2010, which included both pre- and post-intervention threshold shift data [73]. The results of this study show that the average threshold shift was reduced from 1.7 to -0.5 db/year after beginning continuous monitoring utilizing F-MIRE dosimetry, which indicates that use of this method assisted in mitigating exposures to the point that even TTSs were being addressed. When compared to workers at other Alcoa factories, the intervention group achieved a 1.7 dB per year greater reduction in threshold shifts than their peers [73].

Following the involuntary study in Washington, a voluntary study was conducted at three additional Alcoa factories utilizing the same system [52]. Subjects were offered a cash incentive for active participation over the course of 6 months. The results of this study indicate that utilizing daily monitoring with F-MIRE devices significantly reduced the percentage of exposures that exceeded 85 dBA TWA from 14% to 8% and exposures over 90 dBA TWA from 4% to 2%. Additionally, by collecting at-ear measurements and providing that data to workers, work self-efficacy regarding hearing health was improved. Of those who continuously used the F-MIRE dosimeter, “89% believed it helped them control their noise exposure and 96% say it helped them preserve their hearing [52].”

While the Alcoa studies do show consistent support both for the use of frequent exposure monitoring and intervention, and the use of F-MIRE dosimeters as an integral part of a HCP, there are limits to the generalization of these results. First, the subjects of these studies tended to be older and already exhibiting symptoms of NIHL [72, 73]. Research shows that NIHL accelerates at a faster rate during the first 10 to 15 years of exposure [44]. The possibility exists that the reduction in threshold shifts among the subjects could be partially attributed to normal slowing of hearing loss due to age. Second, the noise exposures measured during these studies all came from a manufacturing environment,

where ambient noise levels are rather consistent over a given shift for a given task. Utilizing this system in different work environments or on batch processes may yield different results. Lastly, the use of the F-MIRE dosimeters was paired with a significant training and supervisory intervention regarding proper use of hearing protection [73]. These efforts, rather than the use of the F-MIRE dosimeters, could explain the results of these studies. Therefore, more research utilizing F-MIRE dosimeters in a military population, with types of noise exposures other than manufacturing and in absence of other extensive intervention measures is necessary. Doing so should isolate the effect of F-MIRE dosimeter use and noise exposure feedback to determine if these devices have a significant contribution to preventing NIHL on their own.

Since the Alcoa studies occurred, there has been little additional research utilizing F-MIRE dosimeters in the field. The only other documented research effort occurred in a hospital environment in Brazil among hospital nutrition staff [74]. In addition to the F-MIRE dosimeter, this study measured the ambient noise dose on the shoulder to evaluate the effectiveness of the HPDs worn by the subjects. This study, however, was cross-sectional rather than longitudinal; therefore, no conclusions can be drawn on whether the devices influenced workers noise exposures levels [74].

Given the current state of research concerning F-MIRE noise dosimetry, this thesis effort will focus on utilizing these devices on a military population, over an extended period of time, and on types of noise exposures not typical of a manufacturing environment.

III. Methodology

The following chapter details the procedures used in this effort to collect and analyze worker noise exposure and ACC data. This research was funded under Air Force Institute of Technology FRC grant #2016-244. All procedures involving human subjects, to include questionnaires and collection of individual noise levels, were reviewed and approved by the Institutional Review Board (IRB) for compliance with human subject testing laws and regulations under of oversight of the Wright Research Site IRB. The IRB approval (protocol #FRW20170071H, dated 29 June 2017) is available upon request.

3.1 Equipment

This section lists and describes all the equipment used during this thesis effort, including dosimeters, acoustic calibrator, HPDs and microphones. No deviations from the equipment listed below were noted.

3.1.1 Dosimeters.

The model of dosimeter selected for this study was the QuietDose Exposure Smart Protector Personal Dosimeter produced by Howard Leight/Honeywell. This model was selected for its incorporation of F-MIRE technology, allowing for evaluation of noise levels at the worker's eardrums as well as its built-in method of providing feedback on actual noise levels through LED lights, LCD display, and software reporting features. The QuietDose dosimeter system comes in two types of kits: over-the-ear (earmuffs) and in-the-ear (earplugs). Due to the requirement for combat arms instructors to wear double hearing protection, only the in-the-ear kits were utilized.

The in-the-ear kits come with with a single QuietDose dosimeter (Model number V6) and microphone harness and clip, docking station with USB cable and charger, carrying

pouch, software installation cd, user manual, and Eartip Variety Pack. The contents of the in-the-ear kit are shown in Figure 3.1.



Figure 3.1: In-The-Ear QuietDose Dosimeter Kit Contents

The QuietDose dosimeter is a Type 2 sound level meter, meaning it is only approved for general purpose use and has a implied accuracy of ± 2 dB [64]. They are also sensitive to water and heat; however, these effects are assumed to be negligible for this study as extreme temperatures and humidity were not expected. While dosimeters are the primary method of determining compliance for noise exposures, the QuietDose dosimeter differs from the approved method in the use of the in-ear microphone versus one clipped to the worker's lapel [64]. Given this key difference, the data obtained from this dosimeter system cannot be directly compared to OSHA compliance standards or used as justification for an OSHA citation.

All protocols for utilizing the Quietdose dosimeter functions are available for reference in Appendix A. Throughout the study, there were several equipment malfunctions and software errors that forced changes to the procedure initially devised for this study. These errors are likely attributed to old equipment, provided by the manufacturer from their storage warehouse. This particular product has also been discontinued and the manufacturer no longer provides customer support or device calibration services. Those errors, and their impact on the final results, are discussed below.

3.1.1.1 Equipment and Software Errors and Malfunctions.

The QuietDose dosimeter is intended to operate through a Graphical User Interface (GUI) software suite that manipulates a SQL database on a server or local hard disk. This commercial software was provided with the equipment and used to install the interface and create the database. However, it should be noted that the installation software did not operate as intended and failed to set-up the database and necessary read/write functions without alteration by the researchers. By examining the installation code, it was discovered that each line showed a Chinese character on the end which was not recognized by the SQL code compiler. Removing this character allowed the installation to proceed; however, this change introduced the possibility that some of the functions used by the software may not work as originally intended. While all software functions were observed to work in some limited fashion, there were considerable intermittent software errors that impeded full use of the GUI for data collection. Thus, the provided commercial software was only used for calibration, creating user accounts, and initial device setup, while a third-party software was used to read raw data from the dosimeters directly.

Throughout the course of the study, it was noted by the researchers that the date stored in the dosimeters would intermittently reset to factory conditions when restarted but would then track dates normally from that factory preset date. This device malfunction occurred for most of the dosimeters used and occurred frequently. This time stamp reset often caused

issues with data download utilizing the provided commercial GUI, forcing a work around to retrieve data from the dosimeters. In order to combat this malfunction, the date and time was set prior to performing calibration, though this was rarely successful. On occasions where the device date was reset, the actual date was determined by noting when the device was calibrated and the corresponding factory preset date. The difference between the data log date and the calibration factory preset date was added to the actual calibration date to calculate the actual date for each data entry. This procedure was validated by verifying with the subject the correct date for the data entry. Due to this correction, this device malfunction had no impact on time stamp data quality for this study.

During the course of this study, the researchers encountered numerous issues with all methods of downloading data using the provided commercial software, detailed in Appendix A. When downloading using the immediate or prior shift method, the software would fail to complete the download and provide one of a few error types. All errors appeared to be tied to the dosimeter not retaining date and time information or how many sessions have occurred since the last download. This forced the researchers to utilize the multiple shift method to download data, but even this was not completely effective. For unknown reasons, some shifts would be excluded from those available to download. The error frequency inhibited the researcher's access to data in a timely enough manner to provide worker feedback, thus a more reliable work around method using third party software, CoolTerm, to read raw device data was utilized as the primary data collection method. The provided commercial software was used to verify the data collected using the third party software when possible. For all data points compared, there was no difference in the noise dose data collected by the commercial software and the data collected using CoolTerm.

Many of the devices were not physically calibrated to 114 dB and the device is no longer supported by the manufacturer for re-calibration. While the devices are equipped

with internal calibration capability, there is no method using third party software to extract data on whether the internal calibration was set or to what extent the device has corrected. For those data points that were verified using the commercial software, the internal calibration datum indicates that it was not working for the majority of sessions, despite the majority of devices calibrating high relative to the 114 dB baseline. This means that individual dose and sound level equivalent data will appear higher than actual levels. Additionally, since dose percentages vary logarithmically with decibel exchange rates relative to a threshold sound level, one cannot directly compare mean dose percentages between the control and feedback phase if the calibration is not properly set to a baseline. This effect is negated, however, by considering the difference between the mean sound level TWA for a series of sessions, which are expected to be normally distributed and linear in nature [33]. Therefore, in order to evaluate the effectiveness of noise exposure feedback in reducing noise exposures, the differences in average TWA noise exposures will be used.

While there was no difference in a single device's calibration level for an individual calibration session, there was significant variation in calibration level from session to session, which often exceeded 2 dB. In order to correct for this source of error, any significant reductions in noise exposures were required to exceed the variation in calibration levels before treatment can be considered successful. An analysis of calibration data and its impact on overall results is provided in Section 4.2.

3.1.2 Hearing Protection Devices.

The in-the-ear QuietDose kits come with a variety of earplugs for use with the F-MIRE harness. The earplugs are available in a variety of styles, sizes and NRRs, so as to fit the needs of the individual worker and application. The provided earplugs, shown in Figure 3.2, have NRR and attenuation ratings as described in Table 3.1 [86]. All NRR ratings were tested according to ANSI S3.19-1974 by the manufacturer.



Figure 3.2: F-MIRE Earplugs for QuietDose Dosimeter

From top left to bottom right: SmartFit ET, Acusonix 113 ET, Fusion ET (small and large), 303L ET, Max ET, and MATRIX ET (medium and large)

Table 3.1: QuietDose Earplug Attenuation Ratings in Decibels (Mean/Standard Deviation)

Model Name	NRR	@ 125 Hz	@ 250 Hz	@ 500 Hz	@ 1000 Hz	@ 2000 Hz	@ 3150 Hz	@ 4000 Hz	@ 6300 Hz
<i>SmartFit ET</i>	25	30.1/4.2	30.9/4.4	31.9/3.3	33.5/3.6	33.2/4.0	39.1/4.4	40.6/4.3	43.0/4.3
<i>Fusion ET</i>	25	29.8/4.8	30.2/4.6	31.3/4.0	32.0/2.8	34.6/3.2	37.0/4.8	37.0/4.9	37.8/4.0
<i>Matrix ET</i>	29	32.8/4.6	34.9/3.3	35.6/2.9	37.3/3.2	37.5/2.7	40.4/4.4	39.0/4.7	41.3/4.5
<i>Acusonix 113</i>	30	33.7/3.9	35.8/3.4	36.2/4.0	37.0/3.7	38.9/3.4	42.6/3.9	44.1/4.6	47.3/3.9
<i>303 ET</i>	22	34.9/4.7	31.9/3.9	38.4/3.8	39.6/3.8	39.4/3.8	45.2/4.0	45.6/5.9	47.3/5.2
<i>MAX ET</i>	30	33.9/3.8	31.8/2.4	38.4/3.8	39.8/2.9	40.1/3.7	47.5/4.8	47.2/4.6	49.5/5.2

In addition to the Quietdose Earplugs, the combat arms personnel also utilize double hearing protection with two different types of earmuff protectors. While in the indoor range, a communications headset is utilized whereas an electronic earmuff is used when on outdoor ranges. An example of each of the electronic earmuffs is shown in Figure 3.3 and 3.4, and the attenuation data is provided in Table 3.2.



Figure 3.3: Impact Sport Earmuff



Figure 3.4: Peltor LiteCom Plus Earmuff

Table 3.2: Earmuff Attenuation Ratings in Decibels (Mean/Standard Deviation) [3, 39]

Model Name	NRR	@ 125 Hz	@ 250 Hz	@ 500 Hz	@ 1000 Hz	@ 2000 Hz	@ 4000 Hz	@ 8000 Hz
<i>3M Peltor LiteCom Plus</i>	30	18.3/3.0	24.8/2.8	32.7/2.8	36.2/3.6	35.3/2.5	39.5/3.5	39.4/2.7
<i>Howard Leight Impact Sport</i>	22	18.1/2.7	21.4/1.9	23.5/1.9	27.5/2.0	27.1/1.8	36.8/3.8	39.2/3.9

3.1.3 Acoustic Calibrator.

3.1.3.1 Larson Davis CAL200.

The primary standard used to calibrate the Quietdose equipment is a Larson-Davis Acoustic Calibrator (Model Number CAL200), shown in Figure 3.5, with an operating frequency of 1000 Hz. This device outputs at both 94 dB and 114 dB with a tolerance of ± 0.2 dB [45]. This calibrator is designed for use with 1/2" microphones; however, the QuietDose dosimeter utilizes a microphone much smaller than this inserted into an earplug. In order to use this acoustic calibrator, the dosimeter must be fitted with the Matrix ET large earplug, which has a diameter of approximately 1/2". This method may introduce some error, as all earplugs are not manufactured exactly the same, however, these differences are assumed to be negligible.



Figure 3.5: Larson Davis Acoustic Calibrator

Dosimeter calibration was performed before and after each data collection session in order to ensure reliability of the data collected by each device. Due to how the device was designed, calibration can only be completed utilizing the commercial GUI. Additionally, in

order to maintain consistency between devices, the same microphone harness and earplugs were utilized for the entire duration of the study.

3.1.3.2 G.R.A.S. Pistonphone Type 42AP.

In order to calibrate the blast probe microphone and ATF during the laboratory study, the Type 42AP Pistonphone from G.R.A.S. Sound and Vibration was used. This calibrator operates at 250 Hz and 114 dB with an absolute accuracy of ± 0.9 dB [28]. An adapter was used to interface with the blast probe microphone as shown in Figure 3.6.



Figure 3.6: G.R.A.S. Pistonphone Calibrator with Blast Probe Adapter

3.1.4 Additional Microphone and Probes.

During the laboratory study, two additional lab-grade microphone assemblies were used, detailed in the sections below.

3.1.4.1 67SB Blast Probe Microphone.

In order to read the peak noise levels encountered in the laboratory study without the use of hearing protection, a microphone that is designed to capture impact noise was used.

The G.R.A.S. Type 67SB blast probe microphone is capable of recording impulses up to 174 dB and frequencies between 10 Hz and 20 kHz [30]. The probe was mounted above the ATF, as shown in Figure 3.6.

3.1.4.2 GRAS 45CB Acoustic Test Fixture.

In order to simulate the worker during the laboratory study, a GRAS 45CB ATF was utilized. Like the blast probe microphone, this ATF was designed to capture impulses up to 181 dB [29].

3.2 Laboratory Impact Noise Analysis

Due to large variations in the impact noise group of this thesis effort, it was determined that a lab test of the QuietDose microphone harness was necessary to better understand how it responds to impulses. The microphone harness utilized in the field study was adapted to output to a impulse noise analyzer.



Figure 3.7: Acoustic Test Fixture



Figure 3.8: Impulse Noise Generator

The microphone tests were conducted using an ATF and an impulse noise generator, shown in Figures 3.7 and 3.8. The impulse noise generator is capable of producing sound impulses at 130 to 180 dB using pressurized mylar sheets which are then punctured. To ensure the quality of the waveform as well as to simulate gunfire, a 156 dB impulse (created

using 1 mil mylar sheets pressurized to 70 kPa) was used for most of the tests. The only exception is for ambient conditions, which utilized a 136 dB impulse (created with 0.5 mil mylar sheets pressurized to 25 kPa) to avoid clipping the microphone signal measurements. The ATF was placed approximately 22 inches from and centered on the face of the impulse noise generator. Six distinct microphone response tests(See Figure 3.9), each consisting of 5 impulse measurements, were completed during the lab study:

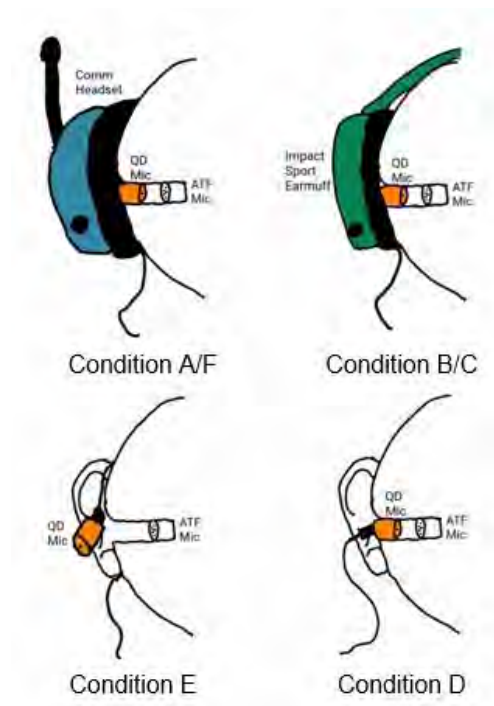


Figure 3.9: Lab Testing Conditions

1. Condition A - Double Hearing Protection w/ Comm Headset in Passive Mode
2. Condition B - Double Hearing Protection w/ Impact Sport Muff in Passive Mode
3. Condition C - Double Hearing Protection w/ Impact Sport Muff in Active Mode
4. Condition D - Single Hearing Protection w/ QuietDose Earplugs Only

5. Condition E - Ambient Noise

6. Condition F - Double Hearing Protection w/ Comm Headset in Active Mode

Each impulse was recorded by the microphones in the ATF as well as the modified microphone harness. The microphones were recorded on two different computers, one using PULSE software and the ATF and blast probe using Texas Instruments software. The key difference between these two setups is that the PULSE records at 262,144 samples per second, as opposed to 200,000 samples per second for the Texas Instruments software. These measurements were compared against each other to determine the limitations of the QuietDose microphone and determine what attenuation is obtainable for the earplugs and earmuffs under laboratory conditions.

3.3 Field Study

The second portion of this research study involved a field study under real operating conditions using volunteers from a population of Combat Arms and Grounds Maintenance personnel on Wright-Patterson Air Force Base. This field study was broken into three distinct phases: recruitment and Personal Attenuation Rating (PAR) testing, control phase, and feedback phase. These phases did not coincide for the two populations of interest and some phases had to be lengthened or shortened due to volunteer schedules, but they follow the same general framework over a duration of no more than 6 months. Each segment of this field study is explained in detail below.

3.3.1 Recruitment and Personal Attenuation Rating Testing.

In the first phase of the field study, volunteers were solicited from a population and an initial test of the effectiveness of the QuietDose HPDs was performed for that individual volunteer. This phase was focused on determining if volunteers could safely proceed with the field study without impacting their ability to perform their normal duties in a high noise environment.

3.3.1.1 Selection and Recruitment of Volunteers.

Volunteers were solicited from a population of active duty and reserve Air Force military and civilian personnel who perform duties in either Combat Arms or Grounds Maintenance. These specific populations were selected due to having regular and significant noise exposures, as well as being colocated at the base where the researchers perform other primary duties. A subject who has met all of the following criteria was considered eligible to volunteer for the field study:

1. Subject must be at least 18 years of age.
2. Subject must be either a Combat Arms Instructor or Equipment Operator at Wright-Patterson Air Force Base.
3. Subject must be an active duty, reservist, or civilian Air Force member. No contractors are permitted to participate.
4. Subject must be projected to continue their duties at Wright-Patterson Air Force Base for a period of not less than 6 months.

Unlike many of the studies performed using the noise exposure feedback [52, 53, 73], participation in this field study was completely voluntary and no incentive for participation or condition for continued employment was provided. While this difference ultimately resulted in less volunteers overall, it also eliminated potential confounding factors that may affect noise exposures in addition to the exposure feedback. In order to participate, subjects read and signed an informed consent agreement and an authorization to access medical records relating to prior hearing loss and audiometric testing. Supervisors were not permitted to be present for or influence volunteering.

3.3.1.2 Personal Attenuation Rating Testing.

After signing the informed consent forms but before starting the field study, the QuietDose HPDs were evaluated for each subject to ensure they could achieve at least

as much attenuation as was required by their HCP. The assumption was made at this point, lacking additional noise exposure characterization data, that this attenuation would be sufficient to protect the worker from the expected noise exposures in their duties. Workers who could not achieve sufficient attenuation on their PAR test with any of the QuietDose HPDs were not permitted to continue the field study.



Figure 3.10: Subject Performing PAR Testing During Recruitment

The PAR test for determining the effectiveness of the HPDs is considered to be the “gold standard” for fit-testing for typical industrial noise [11]. This is primarily because it has many inherent advantages over other methods of fit testing HPDs, including:

1. PAR computations correct for bone-conduction pathways, resonance in the ear canals, and physiological noise-masking.
2. Does not include safety factors and standard-deviation corrections typically included in NRRs due to being computed for a given individual and HPD combination.

3. Accounts for difference in hearing thresholds between ears for an individual.
4. Can be directly subtracted from the dBA sound pressure level to predict an individual's exposure level for the exact noise exposure and HPD.

While PAR tests account for many typical sources of error, they are not without computational uncertainty [11]. Differences between how consistently an individual fits a HPD between sessions can affect how effective the PAR is at predicting a noise exposure level under hearing protection. HPD effectiveness also varies with noise frequency; therefore, it may not be accurate if field noise exposures exhibit a different frequency content. Lastly, there is inherent uncertainty with the measurement method and equipment, though this error is present with all types of fit tests to some extent [11].

3.3.2 Control Phase.

During the control phase of the field study, the baseline noise exposure profiles were established for each individual member without any intervention or treatment by the researchers. Subjects were provided a QuietDose dosimeter to wear during normal duties whenever noise exposures were expected but were not fully informed about the function of the device or its immediate exposure feedback features. Any visual indication of noise exposure levels was obscured using tape for the duration of this phase. Additionally, any data collected was not provided to the subject or discussed with the participants until the start of the feedback phase.

Data downloads and device calibration occurred on a weekly basis with the goal of gathering at least 6 control data points. For some subject groups, achieving 6 control data points was not possible due to conflicts with the study time line and the volunteer's schedules, such as the Air Force Reserve participants who only work one weekend each month. In these cases, a decision to proceed with the feedback phase was made with the understanding that having less than 6 control data points may impact the data analysis and

hinder the ability to determine if any changes in noise exposures between phases were significant.

3.3.3 Feedback Phase.

The original intent for the feedback phase was to provide the field study participants with a computer to download data themselves every shift, thus receiving immediate and constant feedback on noise exposures. However, the frequent data download errors cast doubt on the effectiveness of this treatment plan. If the workers were exposed to frequent device malfunctions, they might put less faith in the feedback received or may even use the device less to avoid the inherent problems. Thus, an equivalent but alternative plan was developed to provide noise exposure feedback to the worker.

At the start of the feedback phase, the subjects were informed of all noise measurements obtained on their assigned equipment and instructed about the full function of the QuietDose device, to include warning lights and LED display information. Noise measurements were provided using a standardized report, shown in Figure 3.11, which provided data on shift length, noise dose percents, 8-hour sound level equivalents, and number of seconds the device read over 115 dB over a shift. The report included detailed explanations of all measurements provided and the subjects were allowed to ask questions about the interpretation of any value on the report.

The standardized report in Figure 3.11 was also used for periodic feedback during the rest of the feedback phase. Due to the schedules of the participants and researchers, providing daily feedback was prohibitively intrusive. Instead, the researchers allowed the participants to use the dosimeters for a period not exceeding one week. At the end of the week, the dosimeters were collected and calibrated, the data for the week was downloaded, an individual report was generated, and the device and report were provided to the subject before the next duty day. At the time of drop-off, the subjects were again allowed to ask questions about the report for that week.

SUBJECT #: *

REPORT DATE: 31 Oct 17

Date	Subject Id	Device	Duration	Dose (OSHA Standard)	Dose (AF Standard)	LEQ (8-hr) dBA	Time > 115(s)
8/1/17	*	10111	2:45	11%	68%	83.3	0
8/2/17	*	10111	6:00	134%	2792%	99.5	247
8/15/17	*	10111	9:04	47%	257%	89.1	0
8/17/17	*	10111	18:00	10%	41%	81.1	1
8/18/17	*	10111	18:00	35%	180%	87.6	1
10/12/17	*	10111	18:00	10%	71%	83.5	0
10/13/17	*	10111	18:00	42%	233%	88.7	1
10/13/17	*	10111	4:50	10%	103%	85.1	1
10/18/17	*	10111	3:11	9%	39%	80.9	0
10/19/17	*	10111	18:00	4%	14%	76.5	0
10/20/17	*	10111	7:10	12%	46%	81.6	0
10/24/17	*	10111	3:42	10%	60%	82.8	0
10/25/17	*	10111	7:57	4%	19%	77.8	0
10/26/17	*	10111	7:31	20%	228%	88.6	14
10/27/17	*	10111	7:43	91%	611%	82.9	7

NOTE: These measurements were obtained using Field Microphone-In-Real-Ear dosimeters. This method is not OSHA authorized for code compliance or recognized by AFI 48-127 as a valid measurement method. These measurements are for research purposes only.

Figure 3.11: Example Noise Report

3.4 Participant Questionnaire

In order to understand worker motivation and health behavior, a 7-point Likert survey was administered at 3 points during the field study: once prior to PAR testing, once at the end of the control phase, and again at the end of the feedback phase. The surveys collected basic subject information (age, rank, gender, etc.), information on typical noise exposures, high noise hobbies, and worker health behavior. The worker health behavior questions were designed to capture both the affective and cognitive aspects of the ACC model. Additionally, questions about the usability of the QuietDose dosimeter were included in the survey administered at the end of the field study. All questions asked during the study are provided in Appendix B.

3.4.1 Creation of the Health Behavior Questions.

The health behavior questions included in the subject survey were written based on job performance research utilizing the ACC model [78]. This framework was chosen because it

was expected to provide the most granularity in responses, as job performance (like hearing protector use) can be evaluated in varying degrees of performance. Questions were written to capture both the affective and cognitive aspects of the ACC model, with roughly half of the questions corresponding to each. Due to job performance not providing an exact analog for health behavior and the measurement used being untested prior, it was determined by the researchers that validation of the affective and cognitive constructs should be completed. This process is detailed in the next section.

3.4.2 Testing Construct Validity.

In order to definitively establish which health behavior questions corresponded to the affective and cognitive aspects of the ACC model, this thesis effort used a procedure very similar to Schleider, Watt, and Greguras' study of the same model [78]. Three subject matter experts were asked to evaluate each health behavior question as either more cognitive or more affective. Only those questions that obtained concurrence among all three experts were utilized in the data analysis. Of the 31 original questions, nine questions were removed, thirteen were determined to be affective focused, and nine were cognitive focused. The questions used in data analysis have been organized according to construct in Appendix B.

3.4.3 Testing Construct Reliability.

For the affect and cognition constructs, reliability of the measure was determined as seen in Table 3.3. Each construct has a Cronbach's alpha exceeding 0.8, which is indicative of a reliable measure. Excluding any one question had no significant impact on the overall reliability of the question set for either affect or cognition.

Table 3.3: Results of Measure Reliability Tests - Affect and Cognition

Affect				Cognition			
α				α			
Entire set	0.8607			Entire set	0.8698		
Excluded Col	α	Excluded Col	α	Excluded Col	α	Excluded Col	α
A1*	0.8643	A8	0.8396	C1	0.8696	C6*	0.8475
A2*	0.8373	A9*	0.8679	C2	0.8562	C7	0.8371
A3	0.8446	A10*	0.8508	C3	0.8565	C8	0.8457
A4*	0.8495	A11	0.8441	C4*	0.8649	C9	0.847
A5*	0.8731	A12*	0.8508	C5*	0.8769		
A6	0.8432	A13	0.8442				
A7*	0.8471						

3.5 Data Analysis

3.5.1 Laboratory Study Data Analysis.

3.5.1.1 Processing the Data for Analysis.

Before any data analysis can be performed on the measurements obtained during the laboratory portion of this thesis effort, it must first be processed to obtain several metrics used to describe impulse noise: $LeqA_{8-hr}$, $LeqC_{8-hr}$, $Leq_{8-hr,100ms}$, Peak sound level, and A-duration. Each of these variables will be used to describe how well the QuietDose microphones perform in response to impulse noise and give insight to the results of the field study measurements for the combat arms instructors. The raw data was processed in MATLAB using CMDR Ed Zechmann's Impulsive Noise Meter application available on MATLAB Central and the Signal Processing Toolkit available for purchase

from MathWorks. The source code used to perform the data processing is available in Appendix C, and performs the following processes:

1. Converts raw data files into column vectors for analysis.
2. Clips QuietDose signals to a one second signal to match the raw ATF and blast probe signal length. Also, clips all signals to a 100 ms signal for calculation of the $Leq_{8-hr,100ms}$ metric.
3. Calculates all impulse noise metrics.
4. Plots the A-weighted sound levels in Pascals versus the time domain.
5. Combines all measurements into a single table for export to Excel.

3.5.1.2 Comparison of Impulse Noise Metric Means for Laboratory Data.

Once the raw data has been processed and all impulse noise metrics have been extracted, the means of the QuietDose microphone can be compared against the microphones in the ATF to determine their relative level of performance. Each impulse noise metric gives important insight into the validity of the measurements obtained by the QuietDose under certain testing conditions, thus each metric must be tested individually. The impulse noise metrics, and the conditions under which they are valid, are summarized in Table 3.4.

For each testing condition and impulse noise metric, the Quietdose and ATF microphone means will be compared against each other. Given that the QuietDose and ATF microphones were paired by the ear they were inserted in for each test, the left and right ears were compared individually. For testing the difference in means for two groups, the 2 sample t-test is the most appropriate statistical method for this analysis. For each test, a two-tailed test with an α of 0.05 was utilized and unequal variances were assumed due to small sample sizes. If the measurements are not found to be significantly different for all

impulse noise metrics, then the QuietDose and ATF microphones will be assumed to have performed similarly in response to impulse noise. Therefore, for each testing condition, ear, and metric combination, the null and alternative hypothesis is as follows:

$$H_0 : \mu_{QD} = \mu_{ATF} \quad H_A : \mu_{QD} \neq \mu_{ATF} \quad (3.1)$$

In Equation 3.1, μ_{QD} is the mean of the QuietDose measurements, while μ_{ATF} is the mean of the measurements taken by the ATF.

Table 3.4: Summary of Impulse Noise Metrics and Assumptions

Metric	Assumptions & Conditions
$LeqA_{8-hr}$	A-Weighted TWA - Not valid over 140 dB; describes human ear response to Gaussian noise (or equivalent) [88]
$LeqC_{8-hr}$	C-Weighted TWA - Describes human ear response to high level noise (over 140 dB) [88]
$Leq_{8-hr,100ms}$	MIL-STD-1474E metric - Uses A-weighting with corrections for long duration impulses
Peak	Highest unweighted sound level measured
A-duration	Width of single peak in seconds

3.5.2 Field Study Data Analysis.

In order to determine if providing worker feedback has a significant effect on noise exposure levels under HPDs, a series of ANOVA tests were performed:

1. Continuous Noise Group - One Way ANOVA blocked by individual - Sound level equivalent by Phase

2. Continuous Noise Group - Full Factorial ANOVA - Sound level equivalent by Phase and Subject ID
3. Impulse Noise Group - One Way ANOVA blocked by individual - Sound level equivalent by Phase
4. Impulse Noise Group - Full Factorial ANOVA - Sound level equivalent by Phase and Subject ID

Each ANOVA test used an α of 0.05 and the residuals were tested for normality and heteroscedascity. Any deviations from normality and equal variance assumptions are noted in Section 4 where they occur. For each ANOVA test, only if the null hypothesis that the control and feedback phase noise exposures are equivalent is rejected can the conclusion be drawn that noise exposure feedback has an effect on worker noise exposures under HPDs.

In order to correct for daily differences in exposure times for the Continuous Noise Group and number of impulses for the Impulse Noise Group, the sound level equivalent was weighted by shift duration or numbers of rounds fired, as appropriate. This procedure was intended to eliminate daily variations in the noise source and isolate the effects of HPD use. The exact calculations used to obtain the weighted sound level equivalents are given in Equations 3.2 through 3.5. If the shift duration or number of rounds could not be reasonably verified, the associated data points were excluded from data analysis.

$$\%D_{hr} = (\%D_{85,3} / \text{shift duration in minutes}) * 60 \quad (3.2)$$

$$Leq_{hr} = 10 * \log_{10}(\%D_{hr}) + 85 \quad (3.3)$$

$$\%D_{1000rounds} = (\%D_{85,3} / \text{number of rounds}) * 1000 \quad (3.4)$$

$$Leq_{1000rounds} = 10 * \log_{10}(\%D_{1000rounds}) + 85 \quad (3.5)$$

For the full factorial ANOVA tests, the factors used were Phase, which represents whether or not the subjects were receiving feedback, and Subject ID, which was meant to

account for individual differences in subjects. The interaction between these factors was also tested. The model used in these tests is shown in Equation 3.6.

$$y = \beta_0 + \beta_1 * Phase + \beta_2 * SubjectID + \beta_3 * Phase * SubjectID \quad (3.6)$$

3.5.3 Analysis of Worker Attitude and Noise Dose Rate.

In the behavioral aspect of the field study, the researchers sought to answer two basic questions: does providing noise exposure feedback improve worker attitude towards hearing protection device use and does worker attitude correlate with improved hearing protection use? The analysis required to address these questions is detailed in the sections below.

3.5.3.1 1-Way ANOVA Analysis of Attitude Constructs versus Phase.

The first question addressed was whether or not providing worker feedback on actual in-ear noise exposure levels correlates with improvements in worker attitude. The researchers hypothesize that having access to data on real noise exposures causes the worker to perform a self-evaluation of their noise hazard risk and draws forward more positive attitudes towards hearing device use. Thus, the researchers expected to see no significant change in either affect, cognition, or affective-cognitive consistency between the initial and midpoint surveys, while an increase in positive attitudes should present itself between the midpoint and final surveys while worker feedback is being administered. In order to support this, an 1-Way ANOVA analysis of the tripartite theory's constructs (affect, cognition and affective-cognitive consistency) versus the time frame of the survey (initial, midpoint and final) was performed. Test significance was evaluated at an α of 0.05 and the residuals were tested for normality and heteroscedascity. Any deviations from normality and equal variance assumptions are noted in Section 4 where they occur.

3.5.3.2 Testing Attitude Moderation of Feedback-Performance Relationship.

In the studies involving the tripartite theory of attitudes, affective-cognitive consistency and its component constructs, affect and cognition, have most frequently been found to act as a moderator of other attitude-behavior relationships [46, 56, 78]. Thus, the researchers predict that affective-cognitive consistency performs a similar role in moderating the effect of receiving noise exposure feedback on their HPD use. Additionally, given that hearing protection use is done for a purpose, it is expected that this task is instrumental and will therefore be better predicted by the cognitive rather than affective component of the tripartite theory of behavior in the case of an attitudinal mismatch. Thus, the moderating effects of affective-cognitive consistency, as well as the affective and cognitive components, require testing to find support for these predictions. The models being tested are depicted in Figure 3.12 and 3.13.

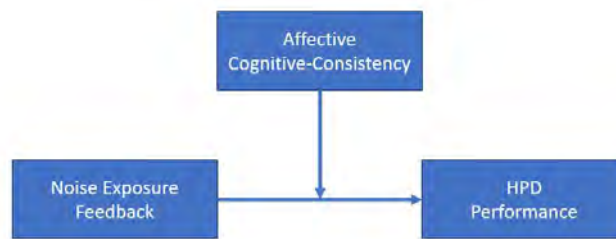


Figure 3.12: Moderation of ACC on Feedback-HPD Performance Relationship

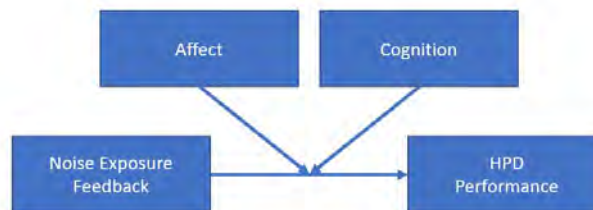


Figure 3.13: Moderation of Affect/Cognition on Feedback-HPD Performance Relationship

Both the models shown will be tested using Full Factorial ANOVA analysis of the noise dose rate obtained in prior analyses versus the tripartite theory constructs and the phase (Control or Feedback). The equations for these models are shown in Equations 3.7 and 3.8. The noise dose rate was operationalized by taking the average noise dose rate for that phase for each individual, while the tripartite constructs are given by the average of the subject's survey results before and after that phase. Impulse and continuous noise groups were evaluated separately, as the duration and round normalized noise dose rates are not equivalent and cannot be directly compared. In order for moderation to be supported, both the Phase as well as the moderating variable should be significant when tested without interaction. A second test, with the interaction between the phase and the moderating variable added, should yield a higher R-squared value as well as a significant interaction term. All ANOVA tests used an α of 0.05 and were evaluated for normality and equal variance assumptions. The results of this analysis are given in Chapter 4.

$$y = \beta_0 + \beta_1 * Phase + \beta_2 * ACC + \beta_3 * Phase * ACC \quad (3.7)$$

$$y = \beta_0 + \beta_1 * Phase + \beta_2 * Affect + \beta_3 * Cognition \\ + \beta_4 * Phase * Affect + \beta_5 * Phase * Cognition \quad (3.8)$$

IV. Results and Discussion

4.1 Participant Demographics and Attrition

4.1.1 Demographics.

Overall, 19 subjects, five grounds maintenance personnel and 14 combat arms instructors, volunteered to participate in the field study portion of this thesis effort. The general demographic makeup of the study population is shown in Figure 4.1. It should be noted that the study population contained more females than is typical of the general Air Force population on HCPs, which is closer to 9% [85]. Additionally, while the majority of volunteers are younger than 40 years of age, there are four individuals that could potentially exhibit normal presbycusis. Only one of those individuals, however, reported being diagnosed with a PTS. Finally, the majority of the study population was sampled from the Air Force Reserves, who express less frequent noise exposures due to their occupation in the Reserves and may have occupational noise exposures in their primary job. Only five individuals reported having a primary occupation that may involve high levels of noise exposure (See Figure 4.3).

The subjects were also asked to describe their typical work week. Their responses are given in Figure 4.2. The majority of the subjects reported a five day work week with between six and ten hour work days. The study population overall reported being noise exposed less days than they typically work, and less hours per day than they typically work. This trend supports the assumption of intermittent noise exposures described in Section 1.5.2 for the study population. The majority of volunteers reported using both earplugs and muffs, which is expected due to the HCP of the combat arms instructors requiring double hearing protection.

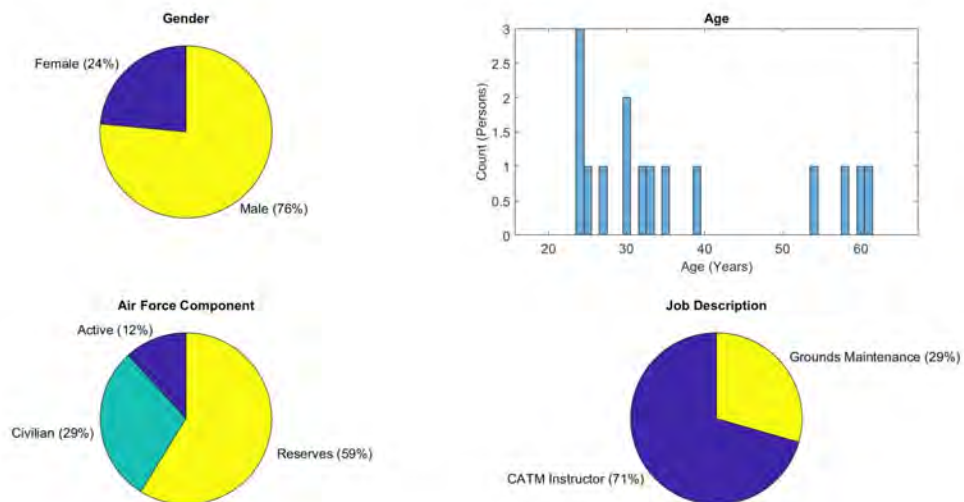


Figure 4.1: Subject Demographics

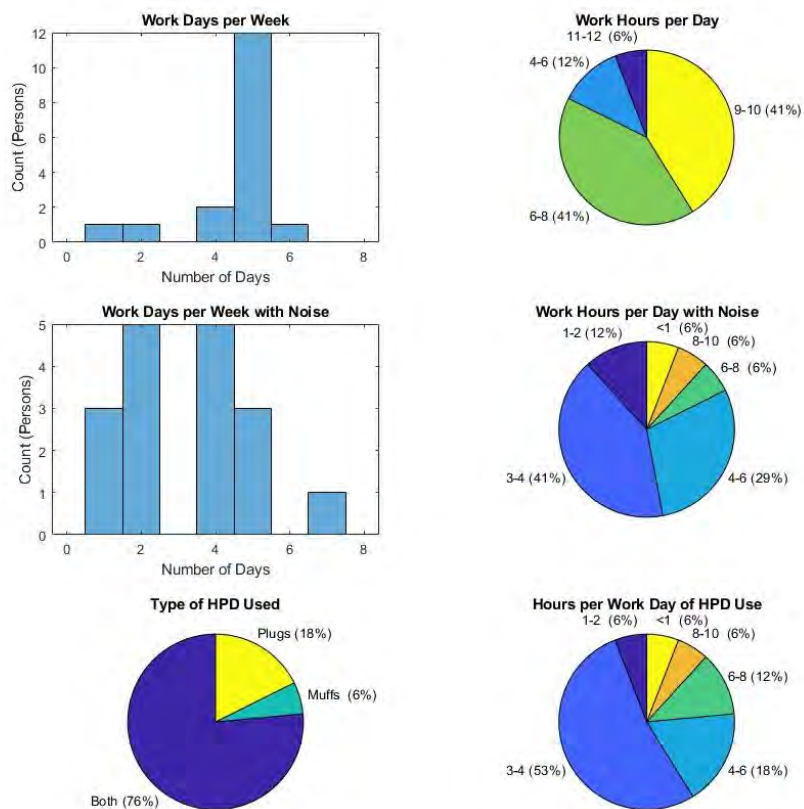


Figure 4.2: Subject Duty Information

In order to describe external factors that may influence this thesis effort, the subjects were also asked about their hobbies and other occupations which may involve high levels of noise exposure. The responses are summarized in Figure 4.3. Over half the study population reported having a noisy hobby, with 60% of those individuals engaging in firearms related activities. This statistic indicates that there are likely high levels of impulse noise that were external to this study and therefore were not measured. Additionally, two individuals reported having firearms related occupations outside of their Air Force duties, while three reported other occupations that involve high levels of continuous noise.

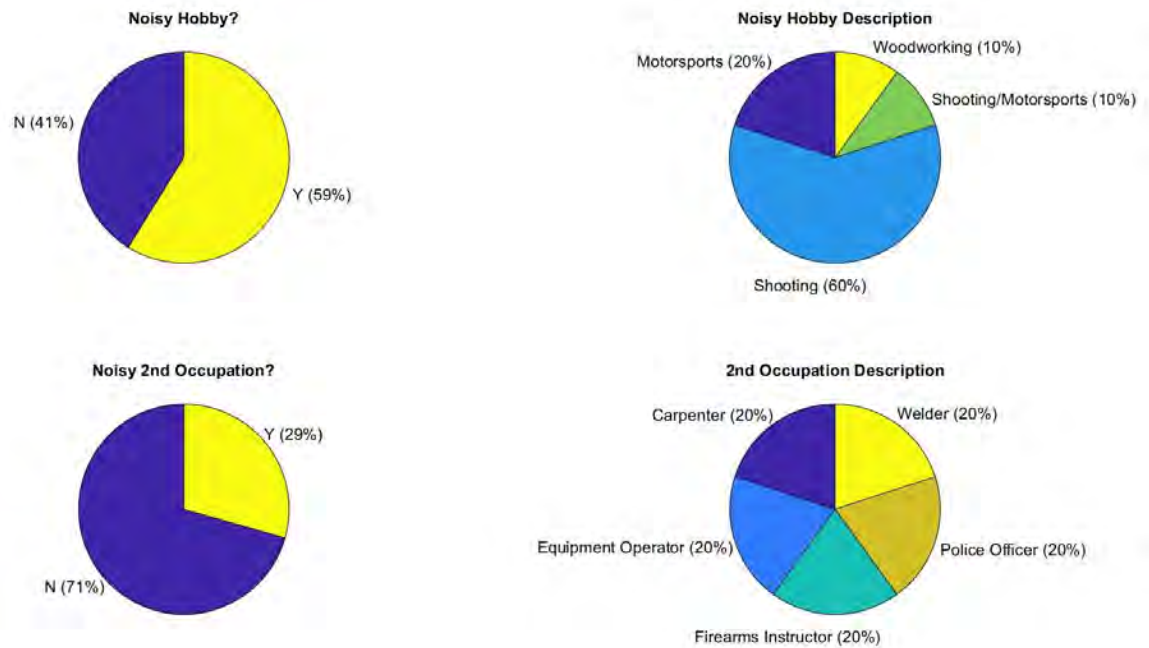


Figure 4.3: Subject External Noise Exposures

4.1.2 Subject Medical History.

In the field study questionnaire, 12% of the subjects reported having been diagnosed with a PTS and 24% with tinnitus (see Figure 4.4). When compared to data obtained from

the Defense Occupational and Environmental Health Readiness System (DOERHS), which contains medical and occupational exposure data for all Air Force Personnel, higher rates of PTS were discovered on record for the same subjects. The exact difference could not be verified due to some subjects declining to provide information required to access their medical records. This difference in reported and recorded PTS rates could be explained by subject's reluctance to provide accurate medical information; however, it could also be attributed to the Air Force's policy to record a PTS if the member does not complete a follow-up exam after identifying a TTS. Of those individuals whose medical records were accessed, one third have a TTS on record.

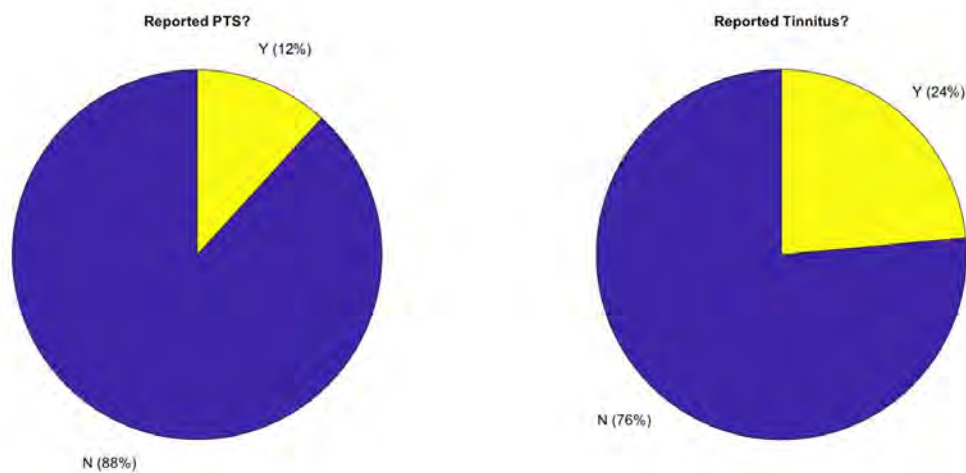


Figure 4.4: Reported Medical History

4.1.3 Personal Attenuation Rating Test Results.

The results from subject PAR testing prior to the field study are given in Figure 4.5. All subjects that received a passing attenuation rating, including those that self-eliminated from the study, are represented. Overall, subjects were able to achieve an attenuation rating between about 22 dB and 35 dB, which falls in the range of ± 5 dB of the earplug NRR.

One subject was able to significantly outperform the NRR, exceeding it by 14 dB. These results indicate, with exception of the one outlier, that the field study population were able to fit their HPDs as well as expected of a normal worker population that has been educated on proper HPD use.

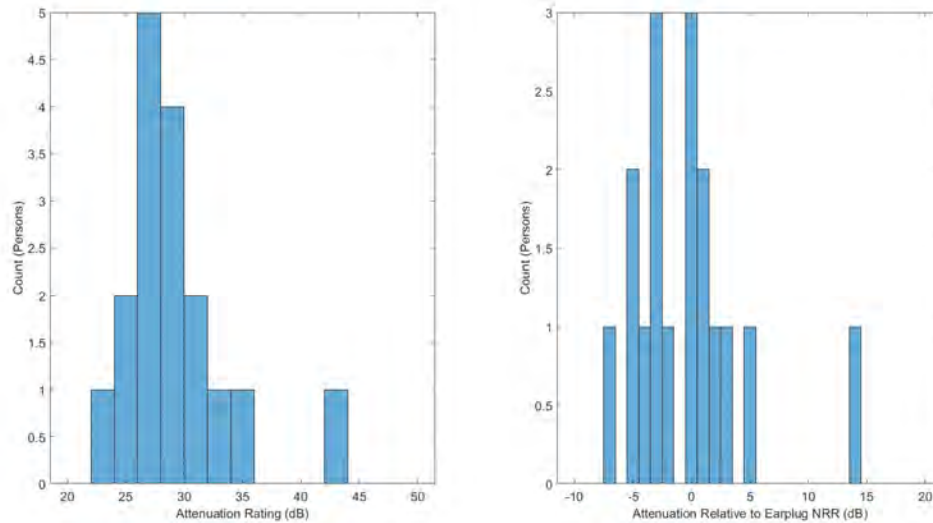


Figure 4.5: Subject PAR Testing Results

4.1.4 Subject Attrition.

Of the 19 subjects who originally volunteered for the study, only 12 were included in the final analysis. Two subjects were eliminated during PAR testing, three subjects self-eliminated during the field study, and two additional subjects were excluded from data analysis due to lack of recorded exposures during the feedback phase. Of the three individuals who self-eliminated, all reported ear discomfort associated with use of the QuietDose earplugs, especially while wearing double hearing protection. The subjects eliminated from the study were not attributable to any one demographic. While the subjects

who self-eliminated were primarily female, the ear discomfort associated with the use of the QuietDose earplug better explains their decision to drop out of the study.

4.2 Calibration Data Analysis

Given the calibration issues discussed in Section 3.1.1.1, it was necessary to determine how much reduction in noise exposure level could be accounted for by device offset. The calibration log data collected during the course of the field study was analyzed for mean calibration level, standard deviation, upper and lower 95% bounds, and expected offset. The device offset was determined by subtracting the normal calibration level of 114 dB from the upper 95% limit. This offset definition provides the most conservative estimate of how much noise exposure is attributable to calibration error. The results of this analysis are given in Table 4.1.

From the results in Table 4.1, three devices had a mean calibration level exceeding 116 dB, the upper limit for Type 2 dosimeters. Taking into account variation in calibration from session to session, eight of the fifteen devices used during this study are considered to exceed normal calibration levels by more than 2 dB. Two devices, 10033 and 10115, have lower 95% limits that are greater than 116 dB, which indicates that those devices would not be expected to ever calibrate in the normal range. One device (10085) had a standard deviation that exceeded 2 dB; however, this device was assigned to a subject that was eliminated from the study. Subjects were assigned a device and harness, which was kept constant throughout the study as device availability allowed, thereby minimizing the impact that differences in device calibration had on feedback quality. Additionally, device calibration differences were present in both phases of the study, therefore should not affect one phase disproportionately from the other. Therefore, any significant reduction in noise levels between phases should still be attributable to the treatment; however, it will be noted if noise dose reductions do not exceed the offset for the device listed in Table 4.1 for any significant result.

Table 4.1: Calibration Analysis Results

Device	Mean	Std Dev.	Lower 95%	Upper 95%	n	Offset
10008	115	0.7071	114.6	115.4	17	1.4
10033	116.7	0.9612	116.2	117.2	15	3.2
10035	114.4	0.8944	113.2	115.5	5	1.5
10042	115.3	1.1595	114.5	116.1	10	2.1
10053	115.2	0.8367	114.2	116.2	5	2.2
10085	113	2.2608	111.3	114.6	10	0.6
10086	115.2	1.3038	113.5	116.8	5	2.8
10102	114.5	0.6742	114.1	114.9	12	0.9
10111	116.2	0.8782	115.8	116.7	18	2.7
10115	118.3	1.0328	117.7	118.8	15	4.8
10117	114.8	0.8367	113.8	115.8	5	1.8
10130	114.8	1.3038	113.2	116.4	5	2.4
10151	115.2	0.4472	114.6	115.8	5	1.8
10153	115.3	1.6838	114.3	116.3	14	2.3
10156	114.8	0.4629	114.3	115.1	8	1.1

4.3 QuietDose Microphone Performance under Lab Conditions

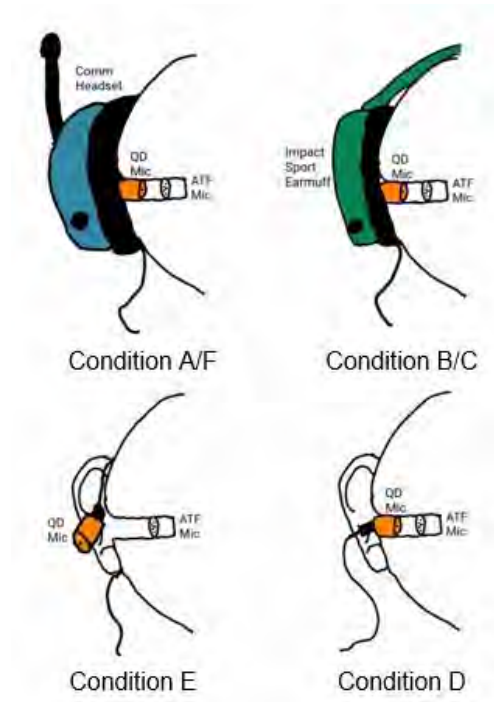


Figure 4.6: Microphone Configurations

Overall, the Quietdose microphone was found to have performed significantly differently than the ATF for the majority of testing conditions (see Figure 4.6 for test conditions), as shown in Table 4.2. There was significant disagreement between the QuietDose microphone and the ATF for all testing conditions in the left ear and all but two testing conditions (A and F) in the right. By examining the A-weighted waveforms (see Figure 4.7), it was found that the QuietDose microphone did not match the ATF in either peak magnitude or phase for any of the tests for the left ear, whereas the right ear did match in phase but not in peak magnitude for most of the tests. Given this observation, it was determined that the QuietDose microphone in the left ear was likely malfunctioning, which would explain the widespread disagreement with the ATF readings. However, equipment

malfunction could not be used to explain the disagreement in right ear measurements for testing conditions B, C, D, or E.

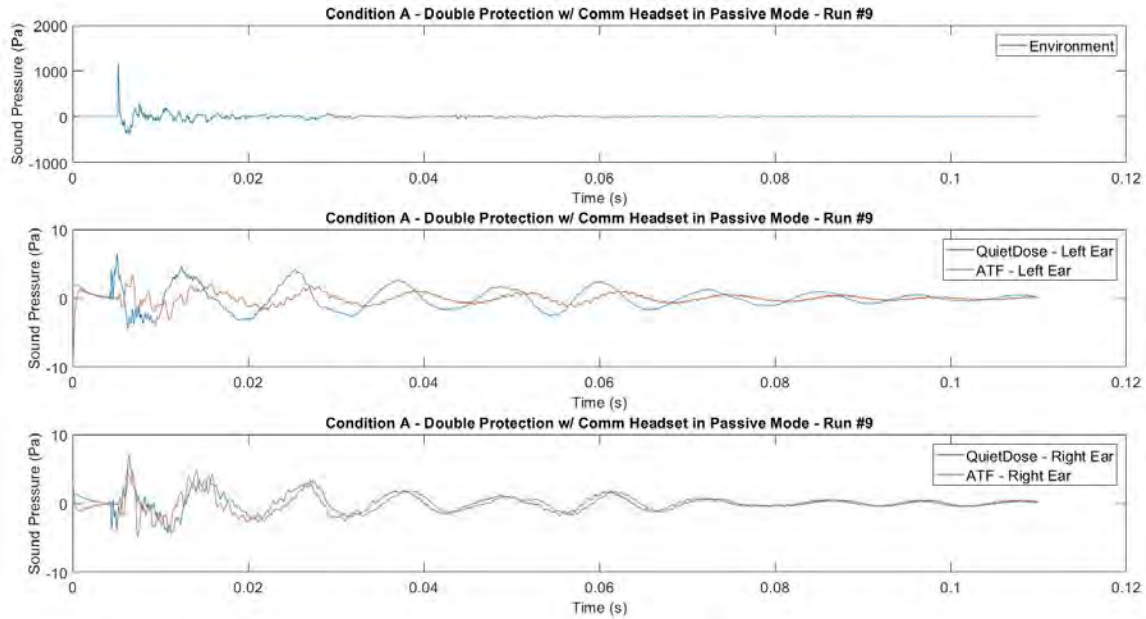


Figure 4.7: Typical A-Weighted Waveform

For the right ear, the only testing conditions that the Quietdose microphone did not vary significantly from the ATF involved double hearing protection with the communications headset. It was observed during testing that a proper seal could not be obtained with the Impact Sport earmuff, due to the earplugs stems protruding and making contact with the inside of the muff. The lack of an airtight seal likely caused leaks which allowed some amount of impulse noise to bypass the earmuffs completely, as depicted in Figure 4.8. Testing conditions D and E, which allowed the impulse to interact with the earplugs in absence of muffs, also showed significant difference in means for all impulse noise metrics. Given these observations, the most likely explanation for the differences in the QuietDose and ATF microphone readings in test conditions B through E is that the QuietDose microphone does not perform as expected when unattenuated impulses are

allowed to contact the earplug or earplug stem. This assertion is further supported by noting that the greatest difference in the means for all metrics occurs for Condition D, which involved single hearing protection and allowed the impulse to interact with earplug and harness assembly unattenuated by earmuffs.

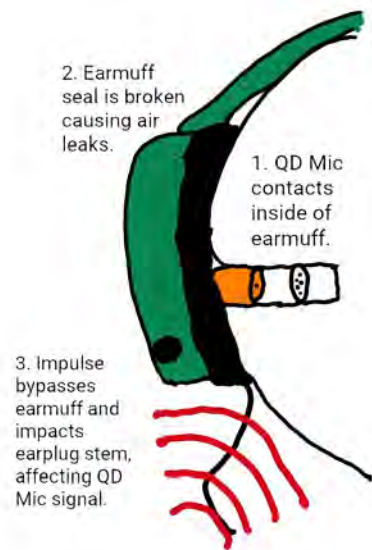


Figure 4.8: QuietDose Microphone Interference from Impulse Bypassing Earmuffs

The implications of these findings on the field study are important considerations in qualifying the results of the impulse noise group. First, the QuietDose performed similarly to the ATF for the communications headset. With exception of one recording session, all measurements were performed using double hearing protection with this HPD. Therefore, the field study measurements can only be assumed valid if the earmuff is worn securely without contacting the earplug stems and the microphone is working properly. However, given the overall equipment errors during both the field and laboratory study, and the lack of information on earmuff fit by the subjects, this assumption cannot be adequately supported.

If either of these conditions are broken, then measurements higher than the actual noise exposure levels should be expected.

Table 4.2: 2-Sample T-test for Microphone Performance Results

	<i>LeqA_{8-hr}</i>		<i>LeqC_{8-hr}</i>		<i>Leq_{8-hr,100ms}</i>		Peak		A-duration	
Condition A	Δ (dBA)	p	Δ (dBC)	p	Δ (dBA)	p	Δ (dB)	p	Δ (ms)	p
Left Ear	9.3	< .0001*	7.2	< .0001*	6.3	< .0001*	6.8	< .0001*	-0.4	0.1521
Right Ear	-0.2	0.7825	-0.4	0.6427	-0.7	0.2634	-0.8	0.2964	0.1	0.2652
Condition B										
Left Ear	11	< .0001*	8.2	< .0001	11	< .0001*	6.1	< .0001*	-1.1	< .0001*
Right Ear	5.2	< .0001*	1.8	.0099*	5.3	< .0001*	0.9	0.0594	-101.3	< .0001*
Condition C										
Left Ear	11.1	< .0001*	8.4	< .0001*	11.1	< .0001*	6.3	< .0001*	-1.2	< .0001*
Right Ear	5.3	< .0001*	2	< .0001*	5.4	< .0001*	1	.0235*	-101.2	< .0003*
Condition D	Δ (dBA)	p	Δ (dBC)	p	Δ (dBA)	p	Δ (dB)	p	Δ (ms)	p
Left Ear	15.2	< .0001*	8.5	< .0001*	16.9	< .0001*	12.2	< .0001*	-102.5	< .0001*
Right Ear	9.8	< .0001*	1.8	0.0344*	9.2	< .0001*	7.1	< .0001*	-101.1	< .0001*
Condition E										
Left Ear	-6.3	< .0001*	-0.1	0.7562	-10.8	.0351*	-4.2	.0074*	-1.5	.0327*
Right Ear	-7.2	< .0001*	-2.6	.0008*	-9.5	.0418*	-7.5	.0003*	-1.1	0.2437
Condition F										
Left Ear	6.3	.0002*	7.2	.0001*	6.4	.0001*	6.6	.0001*	-0.1	0.4508
Right Ear	0.8	0.3742	0.1	0.9566*	-1.4	0.1224	-0.3	0.7386	0.1	0.0665

* indicates significance at an α of 0.05

4.4 Field Study Analysis Results

4.4.1 1-Way ANOVA by Subject.

4.4.1.1 Continuous Noise Group.

According to the ANOVA results shown in Table 4.3, there was no detectable difference between the control and feedback phase noise dose rates for individuals in the continuous noise group. However, two individuals did see a non-significant reduction in the mean hourly dose of 3 dB and 6.4 dB, with p values of 0.1299 and .0757, respectively. Due to the small number of samples for these two subjects, the ANOVA test likely lacked the statistical power to effectively reduce the chance of Type II error occurring. If more samples were available for these individuals, there is a possibility that significance could be achieved. The remaining subjects' noise dose rates between the control and feedback phases were similar, varying by only +/- 1 dB.

4.4.1.2 Impulse Noise Group.

With the exception of one individual, no significant differences could be detected between the control and feedback phases for subjects in the impulse noise group, as shown in Table 4.4. The only significant result was a 10.5 dB increase at a p-value of 0.0083, which is the opposite of the hypothesized effect. Additionally, most of the remaining individuals in the impulse noise group experienced a non-significant increase in their noise dose rate of between 2.1 dB and 5.2 dB. Only one subject had a reduction in noise dose rate recorded of about 8.9 dB; although, only 5 total samples were available for both the control and feedback phase for that subject. Like the individuals in the continuous noise group, the sample size was not large enough to obtain the statistical power necessary to mitigate Type II error. Additionally, the findings during the laboratory study concerning the QuietDose's response to impulse noise that bypasses earmuffs calls the accuracy of the recorded noise levels for impulse-type exposures into question.

Table 4.3: 1-Way ANOVA Analysis Results - Continuous Noise Group Blocked by Subject

Source	DF	SS	Mean Square	F Ratio	Prob > F	Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Subject 1											
Phase	1	111.17438	111.174	3.8459	0.0757	Control	4	82.125	2.6883	76.208	88.042
Error	11	317.97639	28.907			Feedback	9	75.7889	1.7922	71.844	79.733
C. Total	12	429.15077									
Subject 2											
Phase	1	20	20	2.9437	0.1299	Control	5	78.8	1.1657	76.044	81.556
Error	7	47.56	6.7943			Feedback	4	75.8	1.3033	72.718	78.882
C. Total	8	67.56									
Subject 3											
Phase	1	0.314325	0.31433	0.0617	0.8065	Control	12	75.175	0.65158	73.811	76.539
Error	19	96.798056	5.09463			Feedback	9	75.4222	0.75238	73.847	76.997
C. Total	20	97.112381									
Subject 4											
Phase	1	1.93393	1.9339	0.1649	0.6932	Control	5	79.7	1.5315	76.288	83.112
Error	10	117.26857	11.7269			Feedback	7	78.8857	1.2943	76.002	81.77
C. Total	11	119.2025									

* indicates significance at an α of 0.05

Table 4.4: 1-Way ANOVA Analysis Results - Impulse Noise Group Blocked by Subject

Source	DF	SS	Mean Square	F Ratio	Prob > F	Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Subject 1											
Phase	1	206.71875	206.719	14.9255	0.0083*	Control	3	76.7	2.1486	71.442	81.958
Error	6	83.1	13.85			Feedback	5	87.2	1.6643	83.128	91.272
C. Total	7	289.81875									
Subject 2											
Phase	1	13.18561	13.1856	0.677	0.4319	Control	3	77.3667	2.5479	71.603	83.13
Error	9	175.28167	19.4757			Feedback	8	79.825	1.5603	76.295	83.355
C. Total	10	188.46727									
Subject 3											
Phase	1	31.62133	31.6213	0.8244	0.4308	Control	3	76.2667	3.5756	64.887	87.646
Error	3	115.06667	38.3556			Feedback	2	81.4	4.3792	67.463	95.337
C. Total	4	146.688									
Subject 4											
Phase	1	13.60286	13.6029	0.2386	0.6402	Control	2	74.5	5.3392	61.875	87.125
Error	7	399.09714	57.0139			Feedback	7	77.4571	2.8539	70.709	84.206
C. Total	8	412.7									
Subject 5											
Phase	1	95.76533	95.765	0.9537	0.4008	Control	2	84.1	7.0857	61.55	106.65
Error	3	301.24667	100.416			Feedback	3	75.1667	5.7855	56.755	93.58
C. Total	4	397.012									
Subject 6											
Phase	1	7.26	7.26	0.1856	0.6888	Control	3	77.4667	3.6112	67.44	87.493
Error	4	156.49333	39.1233			Feedback	3	79.6667	3.6112	69.64	89.693
C. Total	5	163.75333									
Subject 7											
Phase	1	31.74	31.74	0.4694	0.5309	Control	3	81.5333	4.7477	68.351	94.715
Error	4	270.49333	67.6233			Feedback	3	86.1333	4.7477	72.951	99.315
C. Total	5	302.23333									

* indicates significance at an α of 0.05

4.4.1.3 Full Factorial ANOVA - Continuous Noise Group.

After aggregating all available data, a significant reduction in noise dose rate of 2.5 dB was detected at an α of 0.05 for subjects exposed to continuous-type noise. As seen in Table 4.5, both the individual and the phase (Control vs. Feedback) were found to contribute significantly, while the interaction between subject and phase did not. The overall model had an R-squared value of 0.313 (0.210 adjusted) and the sum of squares for the error was twice that of the model. This indicates that, while the factors included in the model were significant, there are other significant effects that were not measured that may be influencing the outcome. Additionally, the significant effects detected for subject ID highlights the fact that subject background and attitudes may continue to play a large part in worker safety and health behavior.

Table 4.5: Full Factorial ANOVA and Effects Test - Continuous Group

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Model	7	263.58498	37.655	3.0534	0.0099*
Error	47	579.60302	12.332		
C. Total	54	843.188			

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Subject Id	3	3	159.14169	4.3016	0.0092*
Phase	1	1	72.73209	5.8978	0.019*
Subject Id*Phase	3	3	84.31369	2.279	0.0917

* indicates significance at an α of 0.05

Table 4.6: Ordered Differences Report - Continuous Noise Group

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
Subject						
4	3	3.994246	1.28705	1.40504	6.58346	0.0032*
1	3	3.658333	1.30873	1.02551	6.29116	0.0075*
2	3	2.001389	1.409546	-0.8343	4.83703	0.1622
4	2	1.992857	1.56345	-1.1524	5.13811	0.2087
1	2	1.656944	1.581345	-1.5243	4.8382	0.3001
4	1	0.335913	1.473204	-2.6278	3.29962	0.8206
Phase						
Control	Feedback	2.475794	1.019454	0.42492	4.52667	0.019*

* indicates significance at an α of 0.05

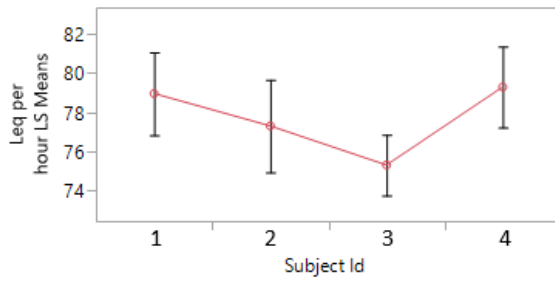


Figure 4.9: Effects Plot - Leq_{hr} By Subject

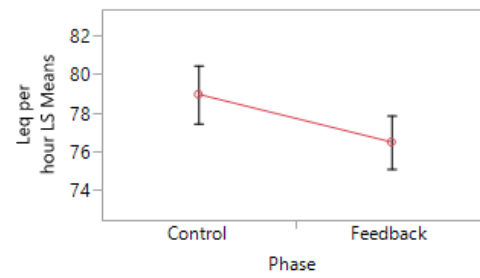


Figure 4.10: Effects Plot - Leq_{hr} By Phase

The detected effects that the individual and noise exposure feedback had on noise dose rates can be seen in Figures 4.9 and 4.10, as well as Table 4.6. One subject experienced significantly lower noise dose rates than two other individuals and about the same level of exposure as the fourth. This individual typically performed noisy tasks more intermittently than the other subjects, which could account for this difference in noise dose rate. While some of the overall noise dose reduction is likely attributable to this one factor, noise exposure feedback still played a significant role. A noise dose rate reduction of 2.5 dB ($p = 0.019$) between the control and feedback phases was found after accounting for individual differences in the subjects. It should be noted that this noise dose reduction does not exceed the calibration offset for the group, which averaged to approximately 2.7 dB.

4.4.1.4 Full Factorial ANOVA - Impulse Noise Group.

Like the analysis performed for individuals, there was no significant effect detected for the impulse noise group as a whole. As shown in Table 4.7, neither subject nor phase appeared to have a measurable impact on noise dose rates. Overall, there was a non-significant increase in noise dose rates for the impulse group of about 2.6 dB between the control and feedback phase. However, as seen in the laboratory study, the QuietDose microphone harness had difficulties accurately capturing impulse noise, instead amplifying the signal if impulses bypass the earmuff and misrepresenting the actual noise level. This effect greatly amplifies the impact of air leaks on measured noise levels, inflating the highest recorded noise levels artificially and increasing the weight those data points had on the final outcome. This effect is not always expected to occur and is difficult to account for without detailed information on the subject's daily earmuff fit. Additionally, some subjects may experience this effect more than others due to physiological differences in ear canal sizes that could make achieving sufficient earplug insertion depth more difficult, thus increasing the likelihood of contact with the earmuff and a broken seal.

Table 4.7: Full Factorial ANOVA and Effects Test - Impulse Group

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Model	13	704.5854	54.1989	1.3001	0.2578
Error	36	1500.7788	41.6883		
C. Total	49	2205.3642			

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Subject Id	6	6	248.49022	0.9934	0.4445
Phase	1	1	77.20216	1.8519	0.182
Subject Id*Phase	6	6	286.79707	1.1466	0.356

** indicates significance at an α of 0.05*

4.5 Worker Attitude Analysis

The 1-way ANOVA analyses, whose results are shown in Table 4.8 and 4.9, produced no indication of any significant change in worker attitude towards HPD use in either of the subject populations. While the lack of significant findings could be a true indication of the actual response, it is also possible that the sample size was too small to detect an effect. Only 12 observations for the continuous noise group and 20 observations for the impulse group were available for analysis. This factor is due primarily to administering the survey only at three time periods during the study. Increasing the number of times the survey is taken would increase the statistical power; however, it may also reduce the quality of the data received if subjects are made to take the same survey too frequently. The better alternative would be to administer the questionnaires to a larger population to reduce risk of Type II error occurring.

Table 4.8: 1-Way ANOVA - Continuous Group - Affect, Cognition, & ACC vs Survey

Continuous	Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Affect						
	Survey	2	2.586785	1.29339	3.5736	0.0721
	Error	9	3.257396	0.36193		
	C. Total	11	5.844182			
Cognition						
	Survey	2	1.705761	0.852881	0.9467	0.4235
	Error	9	8.108025	0.900892		
	C. Total	11	9.813786			
ACC						
	Survey	2	1.92645	0.963225	4.1188	0.0537
	Error	9	2.104737	0.23386		
	C. Total	11	4.031187			

** indicates significance at an α of 0.05*

Table 4.9: 1-Way ANOVA - Impulse Group - Affect, Cognition, & ACC vs Survey

Impulse	Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Affect						
	Survey	2	0.284451	0.142225	0.2846	0.756
	Error	16	7.99459	0.499662		
	C. Total	18	8.279041			
Cognition						
	Survey	2	0.609701	0.30485	0.8198	0.4582
	Error	16	5.949449	0.371841		
	C. Total	18	6.55915			
ACC						
	Survey	2	0.261615	0.130808	0.6503	0.5351
	Error	16	3.218276	0.201142		
	C. Total	18	3.479891			

** indicates significance at an α of 0.05*

Due to limited number of samples, non-parametric tests were also completed. For the majority of tests, similar results were obtained. However, the Wilcoxon Ranked Sums test revealed a significant change in affect ($p = 0.0463$) for the continuous noise group. This difference, however, was determined to be a decrease in affect over the course of the control phase and is not attributable to the effects of noise exposure feedback. During the feedback phase, a non-significant increase was noted, returning subject's reported affect to a similar level as the start of the study.

4.5.1 Moderation of Affect, Cognition and ACC on HPD Performance.

According to the results of the ANOVA analyses given in Tables 4.10 and 4.11, there was no detectable effect of any of the tripartite theory constructs or feedback on average noise dose rates for either the continuous or impulse noise groups. This result could either be a true indicator of the effect, or, like previous analyses, be dependent on lack of statistical power due to small sample size and Type II error. No support was found for the moderating effects of affect, cognition or affective-cognitive consistency on HPD performance, as direct effects were not detected for either the moderator or independent variables.

Table 4.10: Full Factorial ANOVA - Continuous Group - Noise Dose vs Phase & Attitude

ACC	Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
	Model	2	19.0836	9.5418	1.8575	0.2493
	Error	5	25.68515	5.13703		
	C. Total	7	44.76875			
	Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
	Phase	1	1	19.00708	3.7	0.1124
	ACC	1	1	6.832346	1.33	0.3009
Affect/Cognition	Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
	Model	3	22.80286	7.60095	1.3841	0.3689
	Error	4	21.96589	5.49147		
	C. Total	7	44.76875			
	Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
	Phase	1	1	5.775486	1.0517	0.3631
	Affect	1	1	0.353622	0.0644	0.8122
	Cognition	1	1	0.606475	0.1104	0.7563

** indicates significance at an α of 0.05*

Table 4.11: Full Factorial ANOVA - Impulse Group - Noise Dose vs Phase & Attitude

ACC	Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
	Model	2	25.81001	12.905	0.7901	0.4779
	Error	11	179.6621	16.3329		
	C. Total	13	205.4721			
	Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
	Phase	1	1	25.68853	1.5728	0.2358
	ACC	1	1	0.295011	0.0181	0.8955

Affect/Cognition	Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
	Model	3	52.90022	17.6334	1.1557	0.3741
	Error	10	152.5719	15.2572		
	C. Total	13	205.4721			
	Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
	Phase	1	1	30.97322	2.0301	0.1847
	Affect	1	1	0.329066	0.0216	0.8862
	Cognition	1	1	8.674504	0.5686	0.4682

** indicates significance at an α of 0.05*

4.6 QuietDose Usability

When asked to rate the ease of use, effectiveness, and comfort of the QuietDose device itself, respondents generally had a positive impression of the device and the usefulness of the noise reports. However, as seen in Table 4.12, subjects responded negatively to both questions about if they used the immediate feedback to help control noise exposures from moment to moment. This trend is further supported by verbal accounts by the subjects to the researchers. Several individuals reported that the noise reports were useful and interesting, but they were unlikely to check the device during their work shift to see if they were approaching noise exposure limits.

Table 4.12: QuietDose Usability Survey Response Summary

Question Description	Average Score	% Positive Response
QD earplugs are comfortable to wear.	4.9	58%
QD dosimeter is easy to use.	6.2	92%
QD dosimeter interferes with my work performance.	5.2	67%
I check the dosimeter to see what my dose is.	2.7	0%
When the red light comes on, I adjust my HPDs.	3.3	17%
Seeing a noise dose report positively affects my HPD use.	5.2	75%

Overall, the respondents gave the QuietDose dosimeter system a usability score, distributed approximately normally, between 45% and 85% of all possible points (See Figure 4.11). However, it should be noted that the subjects were not given full responsibility for the function of the device, due to data download errors. If the subjects were required to perform their own data collection and encountered similar errors, their overall impression of the device would likely be less than reported in this study.

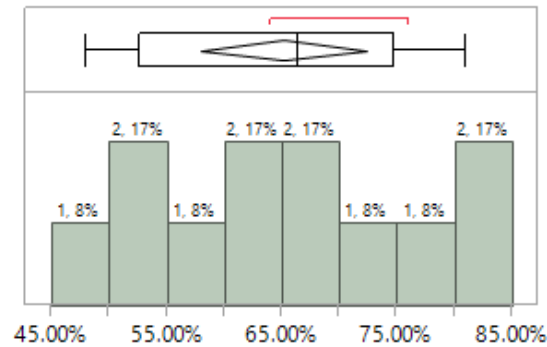


Figure 4.11: Overall QuietDose Usability Score

4.7 Discussion

Overall, this thesis effort found limited support for the use of in-ear dosimetry and periodic noise exposure feedback to improve hearing protection use and reduce occupational noise exposure in continuous noise populations. This effect (-2.5 dB at $p = 0.019$) was only detected at the group level, though the ability to detect significance at the individual level was likely hampered by low numbers of observations per subject. Additionally, individual differences in subjects were also found to significantly affect noise dose rates, highlighting the need to further understand how the subject's characteristics and attitudes impact hearing protection use.

In the impulse noise group, no significant effect was detected between noise exposure feedback and noise dose rates. In addition to small sample sizes, it was found that the QuietDose microphone does not accurately capture impulse noise if the waveform is able to bypass earmuffs and impact the earplug stem directly. While it was not directly tested, this could be an indication that there is structural transmission to the QuietDose microphone that occurs in response to high-level impulse noise. Further research is necessary to confirm this assertion. If structural transmission is occurring, then the highest noise dose rates, obtained when a proper earmuff seal is not attained, would be artificially inflated and not

representative of actual in-ear noise levels. This effect, along with the slow response and peak clipping limitations of dosimeters, limit the usefulness of dosimetry to evaluate and control impulse-type noise exposures. Some advancements in this area have already been made [83] and should continue to be improved upon in order to better understand and explain impulse noise.

This field study was not able to determine if there was a correlation between noise exposure feedback, worker attitude towards hearing protection, and noise dose rates. While no significant effect was detected, this study was limited by low numbers of volunteers leading to lack of statistical power to detect effects, which could be present but small. In order to combat this effect, the researchers could have administered the attitude questionnaire more frequently, but this ultimately would have imposed more on the worker's normal duties and degraded the quality of the data received as subjects become less interested in completing the survey repeatedly.

The overall lack of volunteers, and the impact on number of available data points, was a significant challenge for this study. If this study were to be performed again, the researchers recommend recruiting from a larger pool of volunteers. This, however, was not possible as part of this study due to lack of accessible subjects with significant noise exposures. Additionally, future research could offer incentives for participation; however, this could insert a confounding effect that must be accounted for in the outcome.

Another concern for this study was the limitations of the dosimeter used for data collection. Issues with data download impeded the researcher's ability to take full advantage of the noise dosimeter's feedback function. Ideally, the subject would have access to data on his noise exposures at the end of every shift and be able to reflect on his actions that may have impacted any changes from previous days. However, device errors limited feedback to only weekly or, in the case of the Reserves subjects, monthly. This likely limited the efficacy of the treatment, leading to smaller effect sizes. It should also

be noted that while subjects reported positive impressions of the device and noise reports, few subjects reported taking action during their shift using the immediate feedback features of the device. Therefore, future research and innovations in dosimeter technology should focus on improving usefulness of end-of-shift reporting features over immediate feedback functions. Additionally, other commercial dosimetry devices are available that may be better suited for this type of application. While the QuietDose dosimeter produces data on the daily noise dose, there are some commercial alternatives that provide noise dose level throughout the day. Having access to this additional data may allow the worker to pinpoint the exact task that is contributing most to their overall noise exposures. Future research should incorporate this function to determine if this additional granularity increases the effectiveness of the treatment.

Given the small number of volunteers and the limited populations from which they were recruited, this study has limited generalizability to the overall Air Force population. Subjects were primarily civilian and reserves, and thus may not be representative of the active duty military population whose technicians tend to be younger. Additionally, subjects were recruited from a few shops in only two career fields. Results may vary if the study were extended to other noise-exposed populations, such as aircraft maintainers or flight crew. If follow-on research is done, the researchers recommend recruiting from other populations in the Air Force to better understand the impact of in-ear dosimetry and noise exposure feedback on noise exposures in military personnel.

V. Conclusions

In-ear noise dosimetry and noise exposure feedback could provide a useful tool for evaluating occupational noise exposures and motivating individuals to improve their HPD use in a well-structured HCP. In this research effort, support was found for the correlation between in-ear noise dose reports and noise dose reduction in a population of workers exposed to continuous noise (-2.5 dB at $p = 0.019$). This effect was not detected at the individual level, however, due to limited available data. Further advancements in dosimeter technology and its response to impulse noise is necessary before the efficacy of in-ear dosimetry and periodic noise exposure feedback can be evaluated for impulse noise. While individual differences were found to be a significant contributor to noise dose levels in the continuous noise group, no correlation was detected between a subject's affective or cognitive attitude towards hearing protection and their noise dose rate. Further research is necessary to better understand the link between an individual's attitude and their HPD use. Additionally, while subjects reported positive impressions of the in-ear dosimeter and feedback reports, only a few reported using immediate feedback functions to control their noise dose. Future research on noise dosimetry and its impact on HPD use should emphasize end-of-shift feedback over immediate feedback functions.

This thesis effort was limited by limited numbers of volunteers and reliability of the dosimetry equipment. Follow-on research should attempt to incorporate more subjects from Air Force occupations other than equipment operators and firearms instructors. In order to increase feedback efficacy, the equipment used for data collection should be carefully selected for reliability as well as quality and quantity of noise exposure data provided.

Appendix A: Calibration and Data Download Protocols

A.1 Associating a user with a QuietDose dosimeter

Before a dosimeter can be calibrated and used to collect noise exposure dose information, it must first be associated with a user in the commercial GUI. In order to protect anonymity of the subjects, a single user was created for each dosimeter using generic worker information by using the “Add User” feature. Individual subject’s dosimeter assignments were tracked manually by the researchers. An example of the “Add User” feature and generic user information is shown in Figure A.1. Once the device is matched with a user account, it can then be calibrated and prepared for collection of noise exposure data, which is detailed in the following sections.

The screenshot shows the QuietDose software interface. The main window is titled 'QuietDose' and has a menu bar with 'Settings -> Manage Users'. Below the menu bar is a 'Manage Users' section with a table of existing users. The table has columns for 'Name', 'Employee ID', and checkboxes. The table contains the following data:

Name	Employee ID	
Unit10008	000006	☐
Unit10016	000007	☐
Unit10033	000001	☐
Unit10035	10035	☐
Unit10042	000002	☐
Unit10053	10053	☐
Unit10086	10086	☐
Unit10086	000008	☐
Unit10102	000004	☐
Unit10111	000005	☐

Below the table are 'Add' and 'Delete' buttons. An 'Add User' dialog box is open in the center, with the following fields:

- Select IF Supervisor: ☐
- First name: Unit
- Last name: 20153
- Employee ID: 20153
- Email:
- CC:
- Mobile:
- Text Carrier Extn: None
- Supervisor: Jesse Trawick
- Department: AFTT
- Crew: Research
- Shift: Not Applicable
- Location: Lab

At the bottom of the dialog box are 'Add' and 'Cancel' buttons. The background also shows a 'Locations' section with a table of locations.

Figure A.1: Add/Associate User Screen

To associate a new user account with a QuietDose dosimeter in the SQL database:

1. Connect the USB docking station to the computer.
2. Navigate to the Home screen in the provided commercial GUI.
3. Turn the dosimeter on and wait for it to initialize. Then, place it in the USB docking station and press the “Data” button on the device.
4. The GUI will prompt the researcher to associate a user with the device. Click the “Associate User” button in the GUI.
5. Select the user account corresponding to the device in the list of users and click the “Associate User” button in the lower right-hand corner of the window.
6. The dosimeter is now associated with a user account in the database.

A.2 Setting internal clock and calendar on a Quietdose dosimeter

In order to properly associate a data point with a time and date, the dosimeter must first be synced with clock on the computer used to download the data. This is accomplished by performing the following:

1. Connect the USB docking station to the computer.
2. Navigate to the “Set Date and Time” tab in the provided commercial software.
3. On the dosimeter, press and hold the “ON” and “SPL” buttons simultaneously until the device displays “Communicating... Please Wait.”
4. Place the dosimeter into the USB docking station and click the “Set Date and time” button in the GUI (See Figure A.2). The button text will turn gray while processing the request.

5. Once the button text returns to normal, the date and time have been properly set on the device.

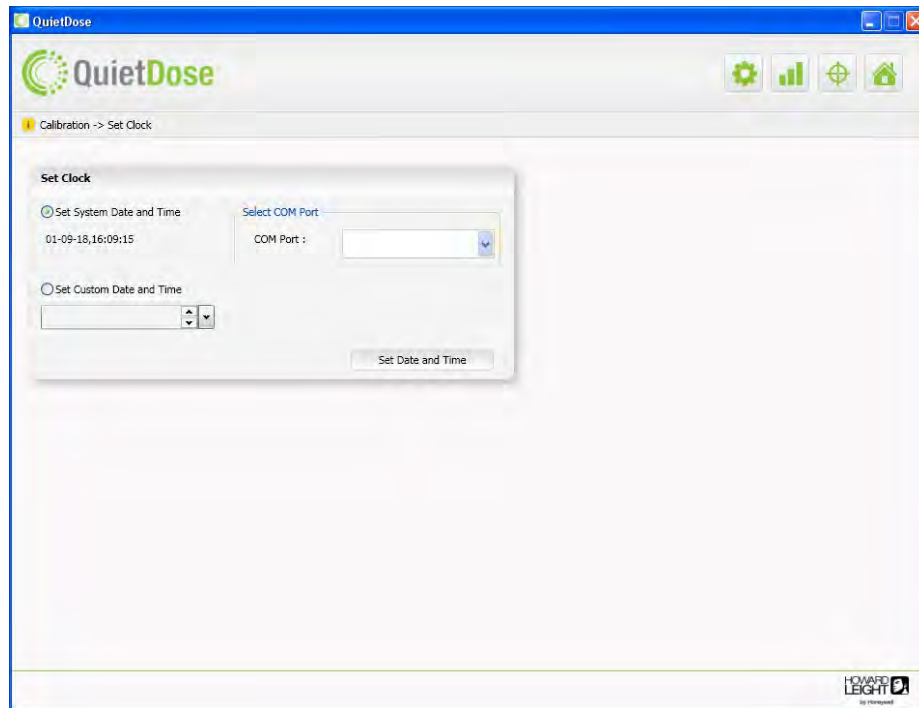


Figure A.2: Set Date and Time Screen

A.3 Calibration of QuietDose dosimeters

1. Set date and time per instructions in Section A.2. Leave the device in the docking station after date and time are synced.
2. After dosimeter completely initializes, navigate to the Calibration Check screen in the commercial GUI, as shown in Figure A.3.
3. Using a Matrix-ET earplug, place the left microphone (short wire) in the acoustic calibrator and turn the calibrator on. Click the “READ” button on the GUI.

4. On the dosimeter press and hold the “DATA” button until the GUI indicates pass or fail.
5. Repeat steps 3 and 4 for the right microphone (long wire).
6. Click the “FINISH” button to store the calibration results.
7. Navigate to the “Calibration History” screen, shown in Figure A.4 and verify calibration data is stored.
8. Compare to other entries for the device. If new calibration data differs from other sessions by more than 2 dB, re-complete steps 2 through 7 to verify calibration.

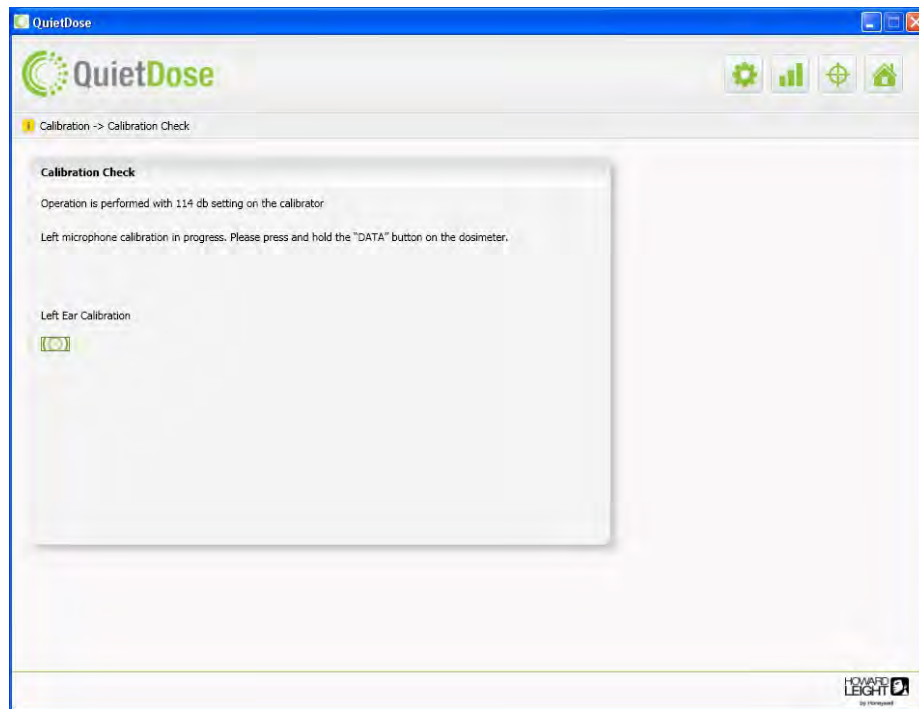


Figure A.3: Device Calibration Screen

Device	Date	Left Ear	Right Ear
10156	9/10/2017 10:15:39 AM	115	115
10156	10/24/2017 8:58:53 PM	115	115
10156	10/31/2017 7:32:04 PM	115	115
10156	11/7/2017 6:50:16 PM	114	114
10156	11/14/2017 8:24:17 PM	115	115
10156	11/21/2017 8:18:02 PM	115	115
10156	12/5/2017 6:46:59 PM	115	115
10156	12/13/2017 10:56:59 AM	114	114
10153	6/2/2017 9:45:00 PM	113	113
10153	6/9/2017 8:48:59 AM	116	116

Figure A.4: Calibration History Screen

A.4 Downloading Data

A.4.1 Using Quietdose Software.

The first method is used to obtain data for the current session and is meant to provide immediate feedback to the worker. At the end of the shift and before shutting down the dosimeter, the worker places the device in the docking station and opens the QuietDose software to its home screen. They then press and hold the data button on the dosimeter until the GUI prompts the user to confirm download. After clicking the confirmation, the data is uploaded and the dose percentage for that shift is briefly flashed to update the worker on how exposed they were for that shift.

The second method is used to retrieve data for the immediate prior shift in the event the device was turned off before downloading the data. In this method, the worker turns on the device while it is still in the docking station and the QuietDose software is open to

the home screen. The device transmits data for 30 seconds before beginning a new session, during which the worker must confirm data download as in the first method. Similarly, the previous shift noise exposure is briefly flashed on the GUI.

The last method is intended to retrieve data for multiple shifts when data download has not occurred for between two and sixteen shifts. This method requires the worker to place the dosimeter in the docking station with the QuietDose home screen showing after the device has initialized completely. The worker then presses the “FN” button on the dosimeter to begin upload. A new window opens showing all shifts on the device that are available for download. The worker checks the relevant shifts and clicks “SAVE” to upload all selected shifts. This method does not provide any immediate worker feedback as to noise exposures for the shifts uploaded.

A.4.2 Using CoolTerm Software.

Access the raw device data using the Coolterm Software by performing the following:

1. Open CoolTerm.exe and navigate to Options. Ensure appropriate Comm port is set in the Options menu (See Figure A.5).
2. Turn on the dosimeter and allow it to fully initialize. Place dosimeter in the docking station and click the “Connect” button on the CoolTerm GUI.
3. Press and hold the “FN” button until data loads on the screen as shown in Figure A.6.
4. Scroll to top of entries and manually record data. For each data line, the first datum is the Session Number, second is the time in seconds, third is the OSHA standard dose in percent, fifth is the Time > 115 dB in seconds, and sixth is the NIOSH standard dose in percent.
5. Scroll down to timestamps. Locate session number and record the time stamp.

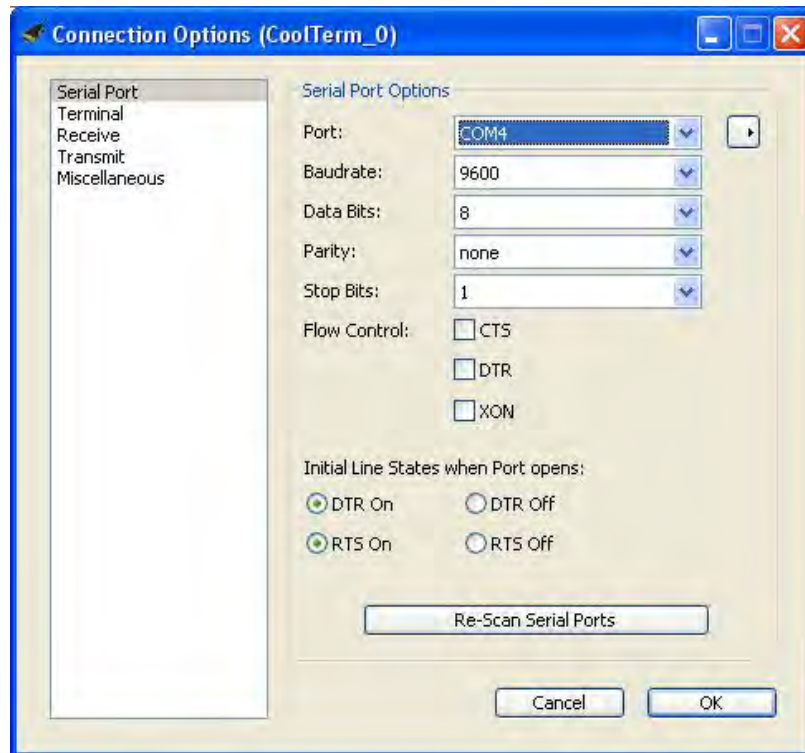


Figure A.5: CoolTerm Connection Options

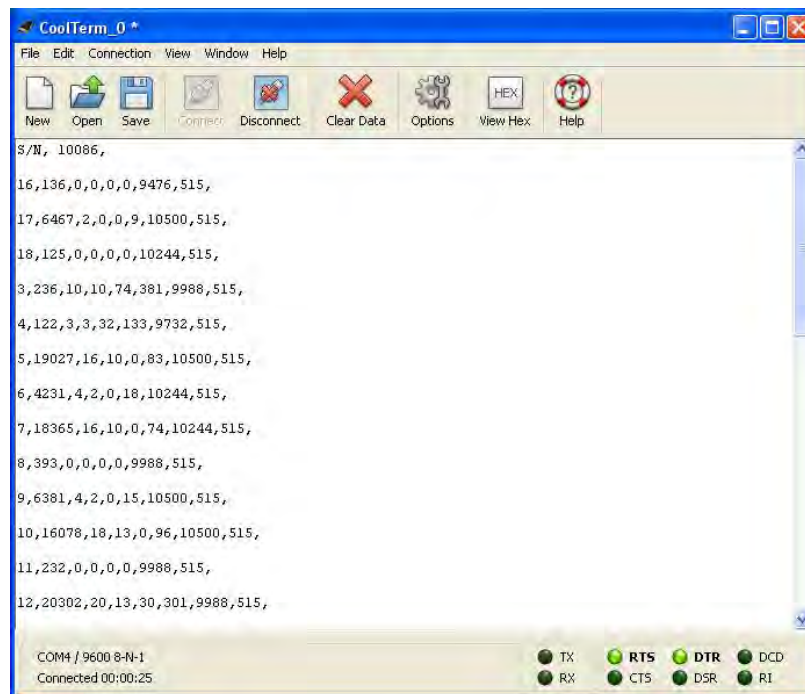


Figure A.6: Raw Data Example in CoolTerm Software

Appendix B: Participant Survey Questions

B.1 Demographics, Medical History and Exposure Information

1. Name
2. Rank
3. Gender
4. Years of Experience in Job
5. Years of Military Service
6. Age
7. Have you been diagnosed with hearing loss or tinnitus? If so, what type and when?
8. Do you have a history of ear infections?
9. Do you have a second occupation that requires the use of hearing protection? If so, please describe.
10. Do you have any hobbies outside of work that are noisy? If so, please list.
11. If you participate in loud hobbies, how likely are you to wear hearing protection during? (*1 - Not likely to 7 - Likely*)
12. How many days per week do you work?
13. How many hours per day do you perform official duties?
14. How many days per week are you exposed to high noise levels?
15. For high noise days, how many hours per day are you exposed to high noise?

16. (For CATM Instructors) As an instructor, how many days per week are you exposed to gunfire noise on average?
17. About how many hours per typical day do you wear hearing protection?
18. What hearing protection do you typically use? (Plugs, Muffs, or Both)

B.2 Affective Attitude Questions

All questions were evaluated on a 7-point Likert scale with 1 being “Strongly Disagree” and 7 being “Strongly Agree”.

1. Putting in earplugs properly is a hassle.
2. I dislike wearing Earplugs.
3. It is worth it to wear uncomfortable earplugs to protect my hearing.
4. There isn't a point to wearing hearing protection.
5. I dislike wearing earmuff hearing protection.
6. I value my hearing more than the average person.
7. I find wearing earplugs uncomfortable.
8. Wearing hearing protection in noisy environments feels natural.
9. I believe that everyone will lose their hearing eventually, regardless of hearing protection use.
10. I find wearing double hearing protection unpleasant.
11. I believe everyone should take care when putting in earplugs.
12. If I can't hear someone in a loud environment, I am fine with removing my earplugs to better hear them.

13. I feel that wearing hearing protection in loud environments at all times is important.

B.3 Cognitive Attitude Questions

All questions were evaluated on a 7-point Likert scale with 1 being “Strongly Disagree” and 7 being “Strongly Agree”.

1. I am likely to correct others who aren’t wearing their hearing protection properly.
2. I am familiar with how to wear earplugs.
3. I know wearing hearing protection in loud environments is important.
4. If I am only in a loud area for a moment, I won’t bother with hearing protection.
5. I tend to forget hearing protection before performing a loud task.
6. I only wear hearing protection when I am reminded to.
7. I always ask for or find hearing protection before entering a loud area.
8. I am diligent about using hearing protection in my normal duties.
9. If I don’t wear earplugs in loud areas all the time, then I will lose my hearing.

B.4 QuietDose Usability Questions

All questions were evaluated on a 7-point Likert scale with 1 being “Strongly Disagree” and 7 being “Strongly Agree”.

1. QuietDose earplugs are comfortable to wear.
2. The QuietDose dosimeter is easy to use.
3. The QuietDose dosimeter interferes with my work performance.
4. I check the lights or display periodically to see what my dose rate is.

5. When the red light on the dosimeter turns on, I adjust my earplugs until the light goes away.
6. Seeing a periodic noise dose report positively affects my hearing protection use.

Appendix C: MATLAB Source Code

```
% Loads reference variables: sampling rates, reference pressure, filter
% weights.

Fs_Pulse = 262144;
Ts_Pulse = 1/Fs_Pulse;

Fs_NI = 2000000;
Ts_NI = 1/Fs_NI;

P_Ref = 2e-5;
type=0;
settling_time=0.1;

% Create Column Vectors for recordings and converts from volts to pascals.
CH1 = Q/.033;
CH2 = A/.022;
CH3 = SP(1,1:2000000);
CH4 = SP(2,1:2000000);
CH5 = SP(3,1:2000000);

% locate peak impulse
[peak1,index1] = max((CH1));
[peak3,index3] = max((CH3));

% index to 10 ms before peak and 100 ms after peak
minindex1 = round(index1 - .010/Ts_Pulse);
```

```

maxindex1 = round(index1 + .100/Ts_Pulse);
minindex2 = round(index3 - .010/Ts_NI);
maxindex2 = round(index3 + .100/Ts_NI);
maxindexA = round(index1 + .990/Ts_Pulse);

%clip signals to 10 ms before peak and 100 ms after peak
RMS_CH1 = rms(CH1(1:minindex1));
RMS_CH2 = rms(CH2(1:minindex1));
CH1_Clip = (CH1(minindex1:maxindex1) + RMS_CH1);
CH2_Clip = -1*(CH2(minindex1:maxindex1) + RMS_CH2);
CH3_Clip = -1*(CH3(minindex2:maxindex2));
CH4_Clip = -1*(CH4(minindex2:maxindex2));
CH5_Clip = -1*(CH5(minindex2:maxindex2));
CH1_ClipA = (CH1(minindex1:maxindexA) + RMS_CH1);
CH2_ClipA = -1*(CH2(minindex1:maxindexA) + RMS_CH2);

% Calculates A-Duration for all channels.
a1 = A_duration(CH1_ClipA, Fs_Pulse, 0);
a2 = A_duration(CH2_ClipA, Fs_Pulse, 0);
a3 = A_duration(CH3, Fs_NI, 1);
a4 = A_duration(CH4, Fs_NI, 1);
a5 = A_duration(CH5, Fs_NI, 1);

% Calculates impulse noise metrics for all channels.
[LeqA1, LeqA81, LeqC1, LeqC81, Leq1, Leq81, peak_dB1, peak_dBA1, peak_dBC1,
peak_Pa1, peak_PaA1, peak_PaC1]=Leq_all_calc(CH1_ClipA, Fs_Pulse);

```

```

[LeqA2, LeqA82, LeqC2, LeqC82, Leq2, Leq82, peak_dB2, peak_dBA2, peak_dBC2,
peak_Pa2, peak_PaA2, peak_PaC2]=Leq_all_calc(CH2_ClipA, Fs_Pulse);
[LeqA3, LeqA83, LeqC3, LeqC83, Leq3, Leq83, peak_dB3, peak_dBA3, peak_dBC3,
peak_Pa3, peak_PaA3, peak_PaC3]=Leq_all_calc(CH3, Fs_NI);
[LeqA4, LeqA84, LeqC4, LeqC84, Leq4, Leq84, peak_dB4, peak_dBA4, peak_dBC4,
peak_Pa4, peak_PaA4, peak_PaC4]=Leq_all_calc(CH4, Fs_NI);
[LeqA5, LeqA85, LeqC5, LeqC85, Leq5, Leq85, peak_dB5, peak_dBA5, peak_dBC5,
peak_Pa5, peak_PaA5, peak_PaC5]=Leq_all_calc(CH5, Fs_NI);

```

```

% Establishes time domain for plots

```

```

T_Pulse = (0:Ts_Pulse:.110);

```

```

T_NI = (0:Ts_NI:.110);

```

```

% A-weights signal for all channels for plots.

```

```

[yA1]=ACweight_time_filter(type, CH1_Clip, Fs_Pulse, settling_time);

```

```

[yA2]=ACweight_time_filter(type, CH2_Clip, Fs_Pulse, settling_time);

```

```

[yA3]=ACweight_time_filter(type, CH3_Clip, Fs_NI, settling_time);

```

```

[yA4]=ACweight_time_filter(type, CH4_Clip, Fs_NI, settling_time);

```

```

[yA5]=ACweight_time_filter(type, CH5_Clip, Fs_NI, settling_time);

```

```

% Plot A-weighted clipped signals.

```

```

subplot(3,1,1);

```

```

plot(T_NI,yA3);

```

```

title('Condition E - Ambient Air Conditions - Run #14')

```

```

legend('Environment');

```

```

xlabel('Time (s)');

```

```

ylabel('Sound Pressure (Pa)');
set(findall(gcf,'-property','FontSize'),'FontSize',16);

subplot(3,1,2);
plot(T_Pulse,yA2,T_NI,yA4);
title('Condition E - Ambient Air Conditions - Run #14')
legend('QuietDose - Left Ear','ATF - Left Ear');
xlabel('Time (s)');
ylabel('Sound Pressure (Pa)');
ylim([-250 250]);
set(findall(gcf,'-property','FontSize'),'FontSize',16);

subplot(3,1,3);
plot(T_Pulse,yA1,T_NI,yA5);
title('Condition E - Ambient Air Conditions - Run #14')
legend('QuietDose - Right Ear','ATF - Right Ear');
xlabel('Time (s)');
ylabel('Sound Pressure (Pa)');
ylim([-250 250]);
set(findall(gcf,'-property','FontSize'),'FontSize',16);

% Calculates Leq100ms 8-hr equivalents.
yA1weight = ((yA1.^2)/(P_Ref^2));
q1 = trapz(T_Pulse,yA1weight);

yA2weight = ((yA2.^2)/(P_Ref^2));

```

```

q2 = trapz(T_Pulse,yA2weight);

yA3weight = ((yA3.^2)/(P_Ref^2));
q3 = trapz(T_NI,yA3weight);

yA4weight = ((yA4.^2)/(P_Ref^2));
q4 = trapz(T_NI,yA4weight);

yA5weight = ((yA5.^2)/(P_Ref^2));
q5 = trapz(T_NI,yA5weight);

if(a1 > .0025)
    Leq100ms1 = 10*log10((1/.11)*q1)-54.6-16.4;
elseif (a1 > .0002)
    Leq100ms1 = 10*log10((1/.11)*q1)-54.6-(15*log10(a1/.0002));
else
    Leq100ms1 = 10*log10((1/.11)*q1)-54.6;
end

if(a2 > .0025)
    Leq100ms2 = 10*log10((1/.11)*q2)-54.6-16.4;
elseif (a2 > .0002)
    Leq100ms2 = 10*log10((1/.11)*q2)-54.6-(15*log10(a2/.0002));
else
    Leq100ms2 = 10*log10((1/.11)*q2)-54.6;
end

```

```

if(a3 > .0025)
    Leq100ms3 = 10*log10((1/.11)*q3)-54.6-16.4;
elseif (a3 > .0002)
    Leq100ms3 = 10*log10((1/.11)*q3)-54.6-(15*log10(a3/.0002));
else
    Leq100ms3 = 10*log10((1/.11)*q3)-54.6;
end

```

```

if(a4 > .0025)
    Leq100ms4 = 10*log10((1/.11)*q4)-54.6-16.4;
elseif (a4 > .0002)
    Leq100ms4 = 10*log10((1/.11)*q4)-54.6-(15*log10(a4/.0002));
else
    Leq100ms4 = 10*log10((1/.11)*q4)-54.6;
end

```

```

if(a5 > .0025)
    Leq100ms5 = 10*log10((1/.11)*q5)-54.6-16.4;
elseif (a5 > .0002)
    Leq100ms5 = 10*log10((1/.11)*q5)-54.6-(15*log10(a5/.0002));
else
    Leq100ms5 = 10*log10((1/.11)*q5)-54.6;
end

```

%Loads all impulse noise measurements into a single table for copying to

%Excel.

```
Measure = [a1, Leq1, Leq81, LeqA1, LeqA81, LeqC1, LeqC81, peak_dB1,  
abs(peak_Pa1), Leq100ms1;  
a2, Leq2, Leq82, LeqA2, LeqA82, LeqC2, LeqC82, peak_dB2,  
abs(peak_Pa2), Leq100ms2;  
a3, Leq3, Leq83, LeqA3, LeqA83, LeqC3, LeqC83, peak_dB3,  
abs(peak_Pa3), Leq100ms3;  
a4, Leq4, Leq84, LeqA4, LeqA84, LeqC4, LeqC84, peak_dB4,  
abs(peak_Pa4), Leq100ms4;  
a5, Leq5, Leq85, LeqA5, LeqA85, LeqC5, LeqC85, peak_dB5,  
abs(peak_Pa5), Leq100ms5];
```

Bibliography

- [1] “The Health Belief Model”. Karen Glanz, Barbara K. Rimer, and K. Viswanath (editors), *Health Behavior and Health Education: Theory, Practice and Research*, chapter 3, 45–62. John Wiley & Sons, 4th edition, 2008. ISBN 978-0-7879-9614-7.
- [2] “Theory of Reasoned Action, Theory of Planned Behavior, and the Integrated Behavioral Model”. Karen Glanz, Barbara K. Rimer, and K. Viswanath (editors), *Health Behavior and Health Education: Theory, Practice and Research*, chapter 4, 67–92. John Wiley & Sons, 4th edition, 2008. ISBN 978-0-7879-9614-7.
- [3] 3M. “3M Peltor LiteCom Plus User Manual”, 2013.
- [4] Albarracín, Dolores, Marta R Durantini, and Allison Earl. “Empirical and Theoretical Conclusions of an Analysis of Outcomes of HIV-Prevention Interventions”. *Current Directions in Psychological Science*, 15(2):73–78, 4 2006. ISSN 0963-7214.
- [5] Allen, Roosevelt, Jr. “AFI 48-127: Occupational Noise and Hearing Conservation Program”, 2016.
- [6] American National Standards Institute. “Method for the Measurement of Real-Ear Protection of Hearing Protectors and Physical Attenuation of Earmuffs, ANSI S3.19-1974”, 1974.
- [7] American National Standards Institute. “Evaluating the Effectiveness of Hearing Conservation Programs, ANSI S12.13-1991”, 1991.
- [8] American National Standards Institute. “Microphone-in-Real-Ear and Acoustica Test Fixture Methods for the Measurement of Insertion Loss of Circumaural Hearing Protection Devices, ANSI S12.42-1995”, 1995.
- [9] American National Standards Institute. “Methods for Measuring the Real-Ear Attenuation of Hearing Protectors, ANSI S12.6-1997”, 1997.
- [10] Berger, E. H. “Methods of measuring the attenuation of hearing protection devices”. *The Journal of the Acoustical Society of America*, 79(6):1655–1687, 6 1986. ISSN 0001-4966.
- [11] Berger, E. H. “What is a Personal Attenuation Rating (PAR)?”, 2010.
- [12] Berger, E. H. and J. E. Kerivan. “Influence of physiological noise and the occlusion effect on the measurement of relear attenuation at threshold”. *The Journal of the Acoustical Society of America*, 74(1):81–94, 7 1983. ISSN 0001-4966.

- [13] Berger, Elliott H. “Hearing Protection Devices”. E. H. Berger, Larry H. Royster, Julia D. Royster, Dennis P. Driscoll, and Martha Layne (editors), *The Noise Manual*, chapter 10, 379–454. American Industrial Hygiene Association, Indianapolis, IN, 5th edition, 2000. ISBN 0-932628-02-9.
- [14] Berger, Elliott H. “Noise Control and Hearing Conservation: Why Do It?” E. H. Berger, Larry H. Royster, Julia D. Royster, Dennis P. Driscoll, and Martha Layne (editors), *The Noise Manual*, chapter 1, 1–17. American Industrial Hygiene Association, Indianapolis, IN, 5th edition, 2000. ISBN 0-932628-02-09.
- [15] Bruce E. Amrein and Tomasz R. Letowski. *PREDICTING AND AMELIORATING THE EFFECT OF VERY INTENSE SOUNDS ON THE EAR: THE AUDITORY HAZARD ASSESSMENT ALGORITHM FOR HUMANS (AHAH)*. Technical report, U.S. Army Research Laboratory, 2015.
- [16] Cacioppo, John T. and Gary G. Berntson. “Relationship between attitudes and evaluative space: A critical review, with emphasis on the separability of positive and negative substrates.” *Psychological Bulletin*, 115(3):401–423, 1994. ISSN 0033-2909.
- [17] Carpenter, Christopher J. “A meta-analysis of the effectiveness of health belief model variables in predicting behavior.” *Health communication*, 25(8):661–9, 12 2010. ISSN 1532-7027.
- [18] Coles, R.R.A., M.E. Lutman, and J.T. Buffin. “Guidelines on the diagnosis of noise-induced hearing loss for medicolegal purposes”. *Clinical Otolaryngology and Allied Sciences*, 25(4):264–273, 8 2000. ISSN 0307-7772.
- [19] Crites, Stephen L., Leandre R. Fabrigar, and Richard E. Petty. “Measuring the Affective and Cognitive Properties of Attitudes: Conceptual and Methodological Issues”. *Personality and Social Psychology Bulletin*, 20(6):619–634, 12 1994. ISSN 0146-1672.
- [20] Davis, Rickie R. and Odile Clavier. “Impulsive noise: A brief review”. *Hearing Research*, 349:34–36, 2017. ISSN 18785891.
- [21] Department of Defense. “MIL-STD-1474E: STANDARD NOISE LIMITS”, 2015.
- [22] Downs, Danielle Symons and Heather A. Hausenblas. “The Theories of Reasoned Action and Planned Behavior Applied to Exercise: A Meta-analytic Update”. *Journal of Physical Activity and Health*, 2(1):76–97, 1 2005. ISSN 1543-3080.
- [23] Dunn, Derek E., Rickie R. Davis, Carol J. Merry, and John R. Franks. “Hearing loss in the chinchilla from impact and continuous noise exposure”. *The Journal of the Acoustical Society of America*, 90(4):1979–1985, 10 1991. ISSN 0001-4966.

- [24] Engdahl, Bo and Kristian Tambs. "Occupation and the risk of hearing impairment—results from the Nord-Trondelag study on hearing loss." *Scandinavian journal of work, environment & health*, 36(3):250–257, 2010. ISSN 1795-990X (Electronic).
- [25] Environmental Protection Agency. "40 CFR Part 211, Subpart B - Hearing Protective Devices", 1979. URL <https://www.law.cornell.edu/cfr/text/40/part-211/subpart-B>.
- [26] Fishbein, Martin. "Attitudes and the prediction of behavior". *Readings in attitude theory and measurement*, 477–492, 1967.
- [27] Goley, G. Steven, Won Joon Song, and Jay H. Kim. "Kurtosis corrected sound pressure level as a noise metric for risk assessment of occupational noises". *The Journal of the Acoustical Society of America*, 129(3):1475–1481, 3 2011. ISSN 0001-4966.
- [28] G.R.A.S. Sound & Vibration. "Pistonphone Type 42AP", 2011. URL www.gras.dk.
- [29] G.R.A.S. Sound & Vibration. "GRAS 45CB Acoustic Test Fixture", 2017. URL https://www.gras.dk/products/product/ss_export/pdf2?product_id=282.
- [30] G.R.A.S. Sound and Vibration. "67SB Blast Probe Microphone Specifications", 2012. URL https://www.gras.dk/files/p/d/pd_67sb_ver_21_march_2012.pdf.
- [31] Green, Charles B. "AFPD 48-1: Aerospace Medicine Enterprise", 2011.
- [32] Haddock, Geoffrey, Gregory R Maio, Karin Arnold, and Thomas Huskinson. "Should Persuasion Be Affective or Cognitive? The Moderating Effects of Need for Affect and Need for Cognition". *Personality and Social Psychology Bulletin*, 34(6):769–778, 6 2008. ISSN 0146-1672.
- [33] Hager, Lee and Carl Johnson. "Noise Stressors". Steven Jahn, William Bullock, and Joselito Ignacio (editors), *A Strategy for Assessing and Managing Occupational Exposures*, chapter 14, 197–204. American Industrial Hygiene Association, Falls Church, VA, 4th edition, 2015.
- [34] Hamernik, Roger P., William A. Ahroon, Robert I. Davis, and SheauFang Lei. "Hearing threshold shifts from repeated 6h daily exposure to impact noise". *The Journal of the Acoustical Society of America*, 95(1):444–453, 1 1994. ISSN 0001-4966.
- [35] Helfer, Thomas M. "Noise-induced hearing injuries, active component, U.S. Armed Forces, 2007-2010." *MSMR*, 18(6):7–10, 6 2011. ISSN 2158-0111.
- [36] Helfer, Thomas M., Michelle Canham-Chervak, Sara Canada, and Timothy A. Mitchener. "Epidemiology of hearing impairment and noise-induced hearing injury among U.S. Military personnel, 2003-2005". *American Journal of Preventive Medicine*, 38(1 SUPPL.):S71–S77, 2010. ISSN 07493797.

- [37] Helfer, Thomas M., Nikki N. Jordan, and Robyn B. Lee. "Postdeployment hearing loss in U.S. Army Soldiers Seen at Audiology Clinics from April 1, 2003, through March 31, 2004". *American Journal of Audiology*, 14(2):161–168, 2005. ISSN 10590889.
- [38] Helfer, Thomas M., Nikki N. Jordan, Robyn B. Lee, Paul Pietrusiak, Kara Cave, and Kim Schairer. "Noise-Induced Hearing Injury and Comorbidities Among Postdeployment U.S. Army Soldiers: April 2003–June 2009". *American Journal of Audiology*, 20(1):33, 6 2011. ISSN 1059-0889.
- [39] Howard Leight by Honeywell. "Howard Leight Impact Sport User Manual", 2014.
- [40] Institute of Medicine. *Noise and Military Service*. National Academies Press, Washington, D.C., 12 2006. ISBN 978-0-309-09949-3. URL <http://www.nap.edu/catalog/11443>.
- [41] Ivanov, Bobi, Michael Pfau, and Kimberly Ann Parker. "The Attitude Base as a Moderator of the Effectiveness of Inoculation Strategy". *Communication Monographs*, 76(1):47–72, 3 2009. ISSN 0363-7751. URL <http://www.tandfonline.com/doi/abs/10.1080/03637750802682471>.
- [42] Kardous, Chucuri A. and Robert D. Willson. "Limitations of Using Dosimeters in Impulse Noise Environments". *Journal of Occupational and Environmental Hygiene*, 1(7):456–462, 7 2004. ISSN 1545-9624.
- [43] Kerr, Madeleine J, Sally L Lusk, and David L Ronis. "Explaining Mexican American workers' hearing protection use with the health promotion model." *Nursing research*, 51(2):100–9, 2002. ISSN 0029-6562.
- [44] Kirchner, D. Bruce, Eric Evenson, Robert A. Dobie, Peter Rabinowitz, James Crawford, Richard Kopke, and T. Warner Hudson. "Occupational Noise-Induced Hearing Loss". *Journal of Occupational and Environmental Medicine*, 54(1):106–108, 2012. ISSN 1076-2752.
- [45] Larson Davis. "CAL 200 Precision Acoustic Calibrator", 2009.
- [46] Lavine, Howard, Cynthia J Thomsen, Mark P Zanna, and Eugene Borgida. "On the Primacy of Affect in the Determination of Attitudes and Behavior: The Moderating Role of Affective-Cognitive Ambivalence". *JOURNAL OF EXPERIMENTAL SOCIAL PSYCHOLOGY*, 34:398–421, 1998.
- [47] Leensen, M. C J, J. C. Van Duivenbooden, and W. A. Dreschler. "A retrospective analysis of noise-induced hearing loss in the Dutch construction industry". *International Archives of Occupational and Environmental Health*, 84(5):577–590, 2011.
- [48] Lie, Arve, Marit Skogstad, Hkon A. Johannessen, Tore Tynes, Ingrid Sivesind Mehlum, Karl Christian Nordby, Bo Engdahl, and Kristian Tambs. "Occupational

noise exposure and hearing: a systematic review”. *International Archives of Occupational and Environmental Health*, 89(3):351–372, 2016. ISSN 03400131.

- [49] Lusk, S L, D L Ronis, and M M Hogan. “Test of the health promotion model as a causal model of construction workers’ use of hearing protection.” *Research in nursing & health*, 20(3):183–94, 6 1997. ISSN 0160-6891.
- [50] Lusk, S L, D L Ronis, M J Kerr, and J R Atwood. “Test of the Health Promotion Model as a causal model of workers’ use of hearing protection.” *Nursing research*, 43(3):151–7, 1994. ISSN 0029-6562.
- [51] Maio, Gregory R, David W Bell, and Victoria M Esses. “Ambivalence and Persuasion: The Processing of Messages about Immigrant Groups”. *Journal of Experimental Social Psychology*, 32(6):513–536, 11 1996. ISSN 00221031.
- [52] McTague, Michael F., Deron Galusha, Christine Dixon-Ernst, Sharon R. Kirsche, Martin D. Slade, Mark R. Cullen, and Peter M. Rabinowitz. “Impact of daily noise exposure monitoring on occupational noise exposures in manufacturing workers”. *International Journal of Audiology*, 52(sup1):S3–S8, 2 2013. ISSN 1499-2027.
- [53] Michael, Kevin, Ed Tougaw, and Ronda Wilkinson. “Role of continuous monitoring in a hearing conservation program”. *Noise and Health*, 13(51):195, 2011. ISSN 1463-1741.
- [54] Millar, Murray G. and Abraham Tesser. “Effects of affective and cognitive focus on the attitude behavior relation.” *Journal of Personality and Social Psychology*, 51(2):270–276, 1986. ISSN 1939-1315.
- [55] Millar, Murray G and Abraham Tesser. “The effects of affective-cognitive consistency and thought on the attitude-behavior relation”. *Journal of Experimental Social Psychology*, 25(2):189–202, 3 1989. ISSN 00221031.
- [56] Millar, Murray G. and Abraham Tesser. “Attitudes and Behavior: the Cognitive-Affective Mismatch Hypothesis”. *ACR North American Advances*, NA-17, 1990.
- [57] Morata, T, D E Dunn, L W Kretschmer, G K Lemasters, and R W Keith. “Effects of occupational exposure to organic solvents and noise on hearing”. *Scandinavian journal of work, environment & health*, 19(4):245–254, 1993. ISSN 0355-3140.
- [58] Murphy, William J and Amir B Khan Peter Shaw. *ANALYSIS OF CHINCHILLA TEMPORARY AND PERMANENT THRESHOLD SHIFTS FOLLOWING IMPULSIVE NOISE EXPOSURE*. Technical report, National Institute for Occupational Safety and Health, Cincinnati, OH, 1998.
- [59] Nakashima, Ann. *A comparison of metrics for impulse noise exposure Analysis of noise data from small calibre weapons [DRDC-RDDC-2015-R243]*. Technical Report November, DRDC Toronto Research Centre, 2015.

- [60] National Institute for Occupational Safety and Health. “Occupational Noise Exposure”, 1998.
- [61] Neitzel, Richard L., Deron Galusha, Christine Dixon-Ernst, and Peter M. Rabinowitz. “Methods for evaluating temporal trends in noise exposure”. *International Journal of Audiology*, 53(sup2):S76–S83, 3 2014. ISSN 1499-2027.
- [62] Norman, Ross. “Affective-cognitive consistency, attitudes, conformity, and behavior.” *Journal of Personality and Social Psychology*, 32(1):83–91, 1975. ISSN 0022-3514.
- [63] Occupational Safety and Health Administration. “Occupational noise exposure, CFR 1910.95”. *Federal Register*, 36(105):10518, 1971.
- [64] Occupational Safety and Health Administration. “Measurements”. *OSHA Technical Manual - Noise*, chapter III, 37–46. Occupational Safety and Health Administration, Washington, D.C., ted 01-00- edition, 1999.
- [65] Pender, N J, S N Walker, K R Sechrist, and M Frank-Stromborg. “Predicting health-promoting lifestyles in the workplace.” *Nursing research*, 39(6):326–32, 1990. ISSN 0029-6562.
- [66] Pender, Nola J. “Heath Promotion Model Manual”, 2011.
- [67] Petty, Richard E., Leandre R. Fabrigar, and Duane T. Wegener. “Emotional Factors in Attitude and Persuasion”. R. J. Davidson, K. R. Scherer, and H. H. Goldsmith (editors), *Handbook of affective sciences*, chapter 39, 752–772. Oxford University Press, 2003. ISBN 9780195377002.
- [68] Price, G R. *The Auditory Hazard Assessment Algorithm for Humans (AHAH): Hazard Evaluation of Intense Sounds*. Technical report, U.S. Army Research Laboratory, 2011.
- [69] Price, G. Richard. “Predicting mechanical damage to the organ of Corti”. *Hearing Research*, 226(1-2):5–13, 4 2007. ISSN 03785955.
- [70] Priester, Joseph R and Richard E Petty. “The Gradual Threshold Model of Ambivalence: Relating the Positive and Negative Bases of Attitudes to Subjective Ambivalence”. *Journal of Personality and Social Psychology Copyright*, 7(3):431–449, 1996.
- [71] Quick, Brian L., Michael T. Stephenson, Kim Witte, Charles Vaught, Steve Booth-Butterfield, and Dhaval Patel. “An examination of antecedents to coal miners’ hearing protection behaviors: A test of the theory of planned behavior”. *Journal of Safety Research*, 39(3):329–338, 1 2008. ISSN 00224375.
- [72] Rabinowitz, Peter M., Deron Galusha, Christine Dixon-Ernst, Jane E. Clougherty, and Richard L. Neitzel. “The dose-response relationship between in-ear occupational

noise exposure and hearing loss”. *Occupational and Environmental Medicine*, 70(10):716–721, 10 2013. ISSN 1351-0711.

- [73] Rabinowitz, Peter M., Deron Galusha, Sharon R. Kirsche, Mark R. Cullen, Martin D. Slade, and Christine Dixon-Ernst. “Effect of daily noise exposure monitoring on annual rates of hearing loss in industrial workers”. *Occupational and Environmental Medicine*, 68(6):414–418, 6 2011. ISSN 1351-0711.
- [74] Rocha, Clayton Henrique, Isadora Altero Longo, Renata Rodrigues Moreira, and Alessandra Giannella Samelli. “Evaluation of the hearing protector in a real work situation using the field-microphone- in-real-ear method”. *CoDAS*, 28(2):99–105, 4 2016. ISSN 2317-1782.
- [75] Ronis, David L., OiSaeng Hong, and Sally L. Lusk. “Comparison of the original and revised structures of the health promotion model in predicting construction workers’ use of hearing protection”. *Research in Nursing & Health*, 29(1):3–17, 2 2006. ISSN 0160-6891.
- [76] Schaal, Nicholas, Jeremy Slagley, Majed Zreiqat, and Helmut Paschold. “Effects of combined exposure to metals, solvents, and noise on permanent threshold shifts”. *American Journal of Industrial Medicine*, 60(3):227–238, 3 2017. ISSN 02713586.
- [77] Schaal, Nicholas Cody, Jeremy M. Slagley, Cynthia McCormick Richburg, Majed M. Zreiqat, and Helmut W. Paschold. “Chemical-Induced Hearing Loss in Shipyard Workers”. *Journal of Occupational and Environmental Medicine*, 60(1):e55–e62, 1 2018. ISSN 1076-2752.
- [78] Schleicher, Deidra J., John D. Watt, and Gary J. Greguras. “Reexamining the Job Satisfaction-Performance Relationship: The Complexity of Attitudes.” *Journal of Applied Psychology*, 89(1):165–177, 2004. ISSN 1939-1854.
- [79] Seixas, N. S., B. Goldman, L. Sheppard, R. Neitzal, S. Norton, and S. G. Kujawa. “Prospective noise induced changes to hearing among construction industry apprentices”. *Occupational and Environmental Medicine*, 62(5):309–317, 5 2005. ISSN 1351-0711.
- [80] Seixas, N. S., S. G. Kujawa, S. Norton, L. Sheppard, R. Neitzel, and A. Slee. “Predictors of hearing threshold levels and distortion product otoacoustic emissions among noise exposed young adults”. *Occupational and Environmental Medicine*, 61(11):899–907, 11 2004. ISSN 1351-0711.
- [81] Seixas, Noah S, Rick Neitzel, Bert Stover, Lianne Sheppard, Patrick Feeney, David Mills, and Sharon Kujawa. “10-Year prospective study of noise exposure and hearing damage among construction workers”. *Occupational and Environmental Medicine*, 69(9):643–650, 9 2012. ISSN 1351-0711.

- [82] Sliwinska-Kowalska, Mariola, Ewa Zamyslowska-Szmytko, Wieslaw Szymczak, Piotr Kotylo, Marta Fiszer, Wiktor Wesolowski, Malgorzata Pawlaczyk-Luszczynska, Marek Bak, and Anna Gajda-Szadkowska. “Effects of Coexposure to Noise and Mixture of Organic Solvents on Hearing in Dockyard Workers”. *Journal of Occupational and Environmental Medicine*, 46(1):30–38, 1 2004. ISSN 1076-2752.
- [83] Smalt, Christopher J., Joe Lacirignola, Shakti K. Davis, Paul T. Calamia, and Paula P. Collins. “Noise dosimetry for tactical environments”. *Hearing Research*, 349:42–54, 6 2017. ISSN 03785955.
- [84] Smoorenburg, G. F. *Assessment of hearing protector performance in impulsive noise. Final Report*. Technical report, 1996.
- [85] Soderlund, Laurel Lloyd, Elizabeth A. McKenna, Katie Tastad, and Marika Paul. “Prevalence of permanent threshold shifts in the United States Air Force hearing conservation program by career field, 20052011”. *Journal of Occupational and Environmental Hygiene*, 13(5):383–392, 2016. ISSN 1545-9624.
- [86] Sperian Hearing Protection LLC. “QuietDose User Manual”, 2013.
- [87] Stewart, Andrew P. “Program Overview and Administration”. Elliott H. Berger, L. H. Royster, J. D. Royster, D. P. Driscoll, and M. Layne (editors), *The Noise Manual*, chapter 6, 149–164. American Industrial Hygiene Association, Indianapolis, IN, 5th edition, 2000. ISBN 0-932628-02-09.
- [88] Sun, Pengfei, Jun Qin, and Wei Qiu. “Development and validation of a new adaptive weighting for auditory risk assessment of complex noise”. *Applied Acoustics*, 103:30–36, 2 2016. ISSN 0003682X.
- [89] Verbeek, Jos H., Erik Kateman, Thais C. Morata, Wouter A. Dreschler, and Christina Mischke. “Interventions to prevent occupational noise-induced hearing loss: A Cochrane systematic review”. *International Journal of Audiology*, 53(sup2):S84–S96, 3 2014. ISSN 1499-2027.
- [90] Veterans Benefits Administration. *VBA Annual Benefits Report Fiscal Year 2014*. Technical report, U.S. Department of Veterans Affairs, 2015.
- [91] Webb, Thomas L. and Paschal Sheeran. “Does changing behavioral intentions engender behavior change? A meta-analysis of the experimental evidence.” *Psychological Bulletin*, 132(2):249–268, 2006. ISSN 1939-1455.
- [92] Wilson, Timothy D., Samuel Lindsey, and Tonya Y. Schooler. “A model of dual attitudes.” *Psychological Review*, 107(1):101–126, 2000.

REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.						
1. REPORT DATE (DD-MM-YYYY)		2. REPORT TYPE		3. DATES COVERED (From — To)		
27-03-2018		Master's Thesis		Aug 2016-Mar 2018		
4. TITLE AND SUBTITLE Occupational Noise Dose Reduction via Behavior Modification Using In-ear Dosimetry Among USAF Personnel Exposed to Continuous and Impulse Noise				5a. CONTRACT NUMBER		
				in house		
				5b. GRANT NUMBER		
				2016-244		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)				5d. PROJECT NUMBER		
Trawick, Jesse A., Captain, USAF				17V906		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)				8. PERFORMING ORGANIZATION REPORT NUMBER		
Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Way WPAFB, OH 45433-7765				AFIT-ENV-18-M-240		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)		
Elizabeth A. McKenna, AuD, CPS/A US Air Force School of Aerospace Medicine 2510 Fifth Street, Bldg. 840 Wright-Patterson AFB, OH 45433 937-938-3245; DSN 798-3245; elizabeth.anne.mckenna.1.ctr@us.af.mil				USAFSAM/PHR		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION / AVAILABILITY STATEMENT						
DISTRIBUTION STATEMENT A: APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED						
13. SUPPLEMENTARY NOTES						
This work is declared a work of the U.S. Government and is not subject to copyright protection in the United States.						
14. ABSTRACT						
The purpose of this research was to investigate the use of in-ear noise dosimetry and worker feedback to reduce noise exposures among combat arms instructors and heavy equipment operators in the Air Force. Specifically, this thesis sought to determine how effectively hearing protection devices (HPDs) are being utilized currently, and whether providing at-ear noise exposure data to workers results in reduced noise exposures or changes in worker attitude. These questions were addressed by performing a six-month field study using dosimeters to record worker noise exposures under HPDs. Subjects served as their own control, receiving feedback in only the latter half of the study. Nineteen subjects volunteered for the study, with both continuous and impact noise represented. The collected noise exposure data was examined for differences between the control and feedback phases that could indicate more effective HPD use using ANOVA analysis. Additionally, a 7-point Likert survey was utilized to examine worker attitude towards HPDs and hearing health, and worker medical histories were examined for evidence of previous noise injuries. This research effort found a significant reduction in noise dose rate (-2.5 dB at $p = .019$) for continuous noise exposed workers following introduction of periodic noise exposure feedback on in-ear noise levels under hearing protection. This effect was not detected at the individual level due to limited samples. No effect was detected in impulse noise-exposed subjects, primarily due to limitations in dosimeter technology and its response to impulse noise. No correlation was found between subjects affective and cognitive attitude components and noise dose rates. Additionally, while subjects reported positive impressions of the in-ear dosimeter and noise exposure feedback, few reported using the immediate feedback functions to control noise exposure levels within a work shift.						
15. SUBJECT TERMS						
Occupational Noise, F-MIRE Dosimetry, Behavior Modification, Noise Exposure Feedback, Hearing Protection						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT	c. THIS PAGE			Dr. Jeremy M. Slagley (ENv)	
U	U	U	UU	127	19b. TELEPHONE NUMBER (include area code)	
					(937) 785-3636 x4632 jeremy.slagley@afit.edu	