Noise induced hearing loss is a subject of growing concern. Over the past 15 years, several well-documented studies have been completed which express the relationships between industrial noise exposure and damage to normal and pathological ears. This research has provided knowledge of considerable importance to developing successful hearing conservation programs. Many studies have presented the necessity of proper use of personal hearing protection devices. However, the accuracy of procedures for testing hearing protection devices remains questionable.

The purpose of this study was to document a need for
increased research on hearing conservation and offer additional information which may help in developing more accurate testing procedures for personal hearing protection devices. The question investigated in this study was: Can the attenuation factors of personal hearing protection devices be measured with probe-ear microphone measurement instruments, with the same accuracy as the present accepted method ANSI standard (ANSI S3.19-1974)? The test procedure used three insert type personal hearing protection devices on 15 human subjects (30 ears), ages 18-41. Each subject was tested with both the subjective test method and the objective test method for each of the three types of hearing protection used. Data collected for each test method was then compared with group mean, as well as the manufacturer's published specifications, to compare accuracy between test methods.

This study determined that the present ANSI S3-1974, subjective test method, provided results which were closer to the manufacturer's published attenuation factors than that data which was recorded using the objective probe-ear microphone instrument. It was noted, even though the mean attenuation factors for the objective test method, that were considerably lower than that of the subjective method, that the overall consistency of data appeared to be more accurate using the objective method. It is recommended that further studies be conducted to provide a better procedure for using the probe-ear microphone evaluation for measuring the attenuation factors of personal hearing protection devices.
A Comparative Study of Two Methods for Measuring Attenuation Values of Personal Hearing Protection Devices

by

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A COMPARATIVE STUDY OF TWO METHODS FOR MEASURING ATTENUATION
VALUES OF PERSONAL HEARING PROTECTION DEVICES

INTRODUCTION

necessity of proper use of a personal hearing protection device (PHPD) are well defined by (Melnick, 1984; Royster, Royster, & Cecich, 1984; Berger, 1986; Cluff, 1986; Schroeter, 1986; Wilde & Humes, 1987). However, the accuracy of procedures for testing hearing protection devices remains questionable (Behar, 1981; Humes, 1982; Middendorf, Luster, Williams, & Smith, 1983; Melnic, 1984; Royster, Royster, & Cecich, 1984; Berger, 1986; Cluff, 1986; Schroeter, 1986; Wilde & Humes, 1987). This paper demonstrates the need for increased research on hearing conservation and documents new information which may help in developing more accurate testing procedures for PHPD's.

Background of the Problem

Research on noise exposure and hearing loss has brought about Federal and State regulations which require the development and implementation of occupational hearing conservation programs (Miller, 1986). The first Federal regulation to protect workers from harmful noise exposure was the Walsh-Healy Public Contracts Act of 1969, which outlined protection of employees exposed to noise while working for companies doing business with the Federal government under contracts of $10,000 or more. The Walsh-Healy act was quickly followed by the Williams-Steiger Act of 1970, where noise limits were established by the Occupational Safety and Health Administration (OSHA) of the
U.S. Department of Labor. This standard required employers to reduce noise exposure to permissible levels by engineering and administrative controls and defined permissible noise levels as 90dB for an eight hour time-weighted average. In areas where engineering and administrative controls were not feasible (i.e., jet engine at take off, or rock crushing equipment, both of which have noise levels which exceed 120 dB), personal hearing protection devices were required (Lipscomb and Taylor, 1978).

In October 1974, the OSHA published a set of proposed regulations in the Federal Register. No worker would be exposed for any period of time to steady sound levels exceeding 115dB, or impulse or impact noise exceeding a peak sound pressure level (SPL) of 140dB. Audiometric tests were required for employees exposed to an eight hour time-weighted average equal to or exceeding 85dBA. Personal hearing protection devices were required to limit the employee's exposure to noise until the appropriate installation of engineering controls or the initiation of administrative controls (Meyer, 1972; Lipscomb and Taylor, 1978).

The most recent hearing conservation amendment was published by the OSHA in the Federal Register on March 8, 1983. This amendment included requirements for noise monitoring, annual audiometric testing, audiometric review by a medical doctor or licensed audiologist, use of personal
hearing protection devices in noise environment of 85dB or greater and on-going employee education training programs related to the noise exposure.

However, in a 2 to 1 decision on November 8, 1984, the U.S. Fourth Circuit Court of Appeals in Virginia, issued an opinion that invalidated the OSHA hearing conservation amendment. In Forging Industries Association and National Arborists Association Inc. vs Secretary of Labor, the plaintiffs alleged that the hearing conservation amendment exceeded the authority of OSHA. Plaintiffs further alleged that hearing loss was an "effect or result", not a "hazard", and therefore, could not be regulated by OSHA. The real issue concerned required action by employers, perhaps even when the hearing loss may not have been the result of noise exposures in the workplace. A variety of non-occupational noise exposures--such as airplanes, hunting rifles, or loud music--create changes in one's hearing, so the court ruled that since the employer cannot be made responsible for any actions not his fault, the amendment was probably unenforceable and therefore invalid (Miller, 1986).

In September, 1985 the Fourth Circuit Court of Appeals chose to re-hear the OSHA's hearing conservation amendment, because makers of this legislation believed this regulation should be implemented and requested another review. The full circuit court in a unanimous decision overturned the earlier ruling to invalidate the hearing conservation amendment, thus fully reactivating the amendment. Thus,
governmental power was introduced to protect the health and welfare of all people from the effects of noise in the workplace (Miller, 1986).

Certain aspects of damage risk criteria may be debatable, but given sufficient intensity and duration of exposure, hearing loss will inevitably occur (Henderson, Hamernick, Dosanjh, & Mills, 1976; Lipscomb, 1978; Lipscomb & Taylor, 1979; Henderson & Hamernick, 1982; Katz, 1985; Sataloff & Sataloff, 1986). The severity of noise-induced hearing loss varies according to the individual's susceptibility, and to the extent and duration of exposure (Henderson, Hamernick, Dosanjh, & Mills, 1976; Lipscomb & Taylor, 1980; Hamernick, Henderson, & Salvi, 1982; Sataloff & Sataloff, 1986).

Factors such as high fevers, oto-toxic medications, and retrocochlear pathologies can cause high-frequency hearing loss similar to that of noise induced high frequency hearing loss, (Katz, 1985). Sataloff and Sataloff (1986) listed the most important features generally characteristic of noise induced hearing loss:

1. The loss must be sensori-neural with damage chiefly to the cochlear hair cells.

2. The patient must have had a history of long term exposure to intense noise levels sufficient to cause the degree and pattern of loss evident in audiologic findings.

3. The loss must have developed gradually over a period of several years.
4. The loss must have developed during the first 8 to 10 years of noise exposure.

5. The loss must have started in the higher frequencies (generally 3000 to 6000 Hz), and must be equal in both ears.

6. Speech discrimination scores, even with a substantial high-frequency hearing loss, must be generally good (over 75%).

Occupational Noise Exposure

The initial result of exposure to noise is demonstrated by a temporary shift in hearing thresholds (Burns, 1971; Kryter, 1973; Henderson & Hemernik, 1982; McFadden & Plattsmier, 1982; Ward & Nielson, 1982). The threshold will shift gradually over time of exposure, ultimately reaching a plateau after about 8 to 12 hours (Melnick, 1976). The level of the plateau will also depend on the stimulus level and frequency characteristics (Burns, 1971; Henderson & Hemernik, 1982; McFadden & Plattsmier, 1982; Ward & Nielson, 1982). As time away from exposure increases, the temporary threshold shift in hearing levels will recover (Burns, 1971; Henderson & Hemernik, 1982; McFadden & Plattsmier, 1982; Ward & Nielson, 1982). With repeated exposures, recovery diminishes and a permanent threshold shift (NIPTS) is exhibited (Lipscomb, 1978).

The problem of occupational noise exposure and the
prevention of NIPTS is not readily resolved (Kryter, 1972; Hemernik, Henderson, & Salvi, 1982; Melnick, 1984). Hearing conservation programs require more than just a decision by employers to develop programs that reduce noise or reduce noise exposure; these programs also require acceptance of the program by the employee (Melnick, 1984; Miller, 1986; Sataloff & Sataloff, 1987).

The first step in controlling occupational noise exposure involves identifying the noise levels that constitute a hazard and those employees who are exposed to the noise (Lipscomb, 1978; Miller, 1986; Sataloff & Sataloff, 1987). If noise elimination through engineering methods is not possible, a hearing conservation program must be implemented and proper hearing protection devices must be used with employees exposed to the potentially damaging noise levels (Snow, 1979; Lipscomb & Taylor, 1979; Humes, 1983).

The matter of a comprehensive hearing conservation program is, of course, an important part of any effort at hearing conservation, and is a large matter in itself. In this paper, however, the discussion is confined to studies which involve personal hearing protection devices, including the effectiveness of personal hearing protection devices, and methods by which the effectiveness of noise attenuation for the devices may be measured.

Two basic types of personal hearing protection devices are now available: **insert earplugs** (either pre-molded,
formable, or custom molded), or ear muffs, which come in over-the-head styles as well as those which attach to safety helmets. The real protection provided by hearing protection devices is difficult to measure because of the many variables that can contribute to fitting of the device and its attenuation capabilities (e.g., proper insertion, user willingness to wear the device correctly, age, and how clean the instrument is), (Lipscomb & Taylor, 1978; Lipscomb, 1978; Miller, 1986; Sataloff & Sataloff, 1987; Berger, 1986). Many attempts have been made to develop an effective rating system for hearing protection devices, but no system now used provides adequate measurement of hearing protection on all people in all environments (Michael & Bienvenue, 1980; Smith, Broughton, Wilmoth & Mozo, 1983; Royster & Royster, 1985). The method now used to rate the effectiveness of a hearing protection device was derived by the Environmental Protection Agency (EPA), requires establishment of hearing threshold levels with the ear non-occluded, then with the hearing protection device inserted an occluded hearing threshold level measurement is taken. Measurements of occluded-minus non-occluded levels are then used to determine the noise attenuation afforded by the PHPD (Sataloff & Sataloff, 1987). This classification of attenuation rating is known as the Noise Reduction Rating (NRR). EPA requires that all hearing protection devices have the NRR clearly printed on the package or container in which they are dispensed.
The Hearing Conservation Amendment (OSHA, 1985) requires anyone using personal hearing protection devices to subtract 7dB from the manufacturer's printed noise reduction rating to adjust for the difference between the C-weighted scale (the method used to measure sound pressures) and the A-weighted scale, designed to measure sound levels as they are heard by the human ear, the method often used to establish noise exposure levels in hearing conservation programs (Lipscomb & Taylor, 1978; Abel, Alberti, & Riko, 1982). OSHA considers the NRR developed by the EPA to be the most convenient method of assessing the attenuation effectiveness of PHPD's. The NRR system, a single-number rating system that a number of studies have supported as being a workable compromise, prevents underprotection as well as overprotection of noise exposure to the worker (Johnson & Nixon, 1974; Waugh, 1976; Berger, 1979; Sadler & Montgomery, 1982; Middendorf, Luster, Williams, Smith, 1983; Royster, Royster, & Cecich, 1984; Cluff, 1986; Schroeter, 1986; Wilde & Humes, 1987). The NRR is subtracted from the unprotected sound level measured on the C-scale, to yield an effective A-weighted sound exposure level for the worker. The NRR is the difference between the overall C-weighted sound level of a noise spectrum and the resulting A-weighted noise levels under the protector (Berger, 1979).
Introduction of the Hypotheses

In 1957, the American National Standards Institute published the USAS Z24.22-1957 Method for the Measurement of the Real-Ear Attenuation of Ear Protectors at Threshold. In August, 1974, a revision of this standard was introduced and later published as an ANSI standard (ANSI S3.19-1974), Method for the Measurement of Real-Ear Protection of Hearing Protectors and Physical Attenuation of Ear Muffs (Abel, Alberti, & Riko, 1981). This revised standard was used as the guide for the test protocol employed in the study reported here.

In the early 1980's, new equipment became available to audiologists and hearing aid dispensers who were interested in providing in-office probe ear microphone measurements. The professional practitioner thus could determine the acoustical parameters of the ear canal under various conditions. The introduction of probe microphone test equipment (often referred to as real-ear measurement instruments) enabled measurement within the external auditory meatus. This type of equipment has been used in many studies to measure the attenuation values of personal hearing protection devices (Lempert & Edwards, 1983; Royster, Royster, & Cecich, 1984; Berger, 1986; Schroeter, 1986; Cluff, 1986; Savell & Toothman, 1987).

The question investigated in this study was: can the attenuation factors of personal hearing protection devices
be measured with probe-ear microphone measurement instrument with the same accuracy as the present accepted method (ANSI, 1974)?

Statement of the Hypotheses

The protocol for the ANSI S3.19-1974 (ANSI, 1974) was used for the subjective testing procedures to insure accuracy in the comparison of the effectiveness of the probe microphone measurement instrument to the ANSI approved method for testing hearing protection devices.


$H_a$ - The ANSI S3.19-1974 method for Measurement of Real-Ear Protection of Hearing Protectors and Physical Attenuation of Earmuffs will provide data which will show a difference from manufacturer's EPA Noise Reduction Rating as specified for the E.A.R. brand insert earplugs.

2. $H_0$ - Using the ANSI S3.19-1974 protocol, the probe microphone measurement instrument will provide data which will show no difference from manufacturer's EPA Noise Reduction Rating as specified for the E.A.R. brand insert earplugs.

$H_a$ - Using the ANSI S3.19-1974 protocol, the probe
microphone measurement instrument will provide data which
will show a difference to manufacturer's EPA Noise Reduction
Rating as specified for the E.A.R. brand insert earplugs.

3.  \( H_0 \) - The ANSI S3.19-1974 method for Measurement of
Real-Ear Protection of Hearing Protectors and Physical
Attenuation of Earmuffs will provide data which will show no
difference from manufacturer's EPA Noise Reduction Rating as
specified for the MAX brand insert ear plug.

\( H_a \) - The ANSI S3.19-1974 method for Measurement of
Real-Ear Protection of Hearing Protectors and Physical
Attenuation of Earmuffs will provide data which will show a
difference from manufacturer's EPA Noise Reduction Rating as
specified for the MAX brand insert ear plug.

4.  \( H_0 \) - Using the ANSI S3.19-1974 protocol, the probe
microphone measurement instrument will provide data which
will show no difference from manufacturer's EPA Noise
Reduction Rating as specified for the MAX brand insert ear
plug.

\( H_a \) - Using the ANSI S3.19-1974 protocol, the probe
microphone measurement instrument will provide data which
will show a difference from manufacturer's EPA Noise
Reduction Rating as specified for the MAX brand insert ear
plug.

5.  \( H_0 \) - The ANSI S3.19-1974 method for Measurement of
Real-Ear Protection of Hearing Protectors and Physical
Attenuation of Earmuffs will provide data which will show no
difference from manufacturer's EPA Noise Reduction Rating as
specified for the 3M6300 brand insert ear plug.

\(H_a\) - The ANSI S3.19-1974 method for Measurement of Real-Ear Protection of Hearing Protectors and Physical Attenuation of Earmuffs will provide data which will show a difference from manufacturer's EPA Noise Reduction Rating as specified for the 3M6300 insert ear plug.

6. \(H_0\) - Using the ANSI S3.19-1974 protocol, the probe microphone measurement instrument will provide data which will show no difference from manufacturer's EPA Noise Reduction Rating as specified for the 3M6300 brand insert ear plug.

\(H_a\) - Using the ANSI S3.19-1974 protocol, the probe microphone measurement instrument will provide data which corresponds from manufacturer's EPA Noise Reduction Rating as specified for the 3M6300 brand insert ear plug.

7. \(H_0\) - The mean of the test \((X)\) (ANSI S3.19-1974) will not be significantly different from the mean of the test \((Y)\) (probe microphone measurement instrument).

\(H_a\) - The mean of the test \((X)\) (ANSI S3.19-1974) will be significantly different from the mean of the test \((Y)\) (probe microphone measurement instrument).

Definition of Terms

The following terms are defined to provide clarity to their use in the text of this study.

1. Ambient noise: Noise within the environment,
usually the composite of sounds within the range of hearing.

2. **Attenuate**: To reduce sound.

3. **Audiogram**: The graphic representation of the acuity of a subject's hearing.

4. **Audiometer**: An instrument designed to test hearing acuity.

5. **Auditory fatigue**: A temporary increase in the hearing acuity or threshold of audibility resulting from previous auditory stimulation.

6. **Decibel (dB)**: The measurement of the amplitude of sound based on a logarithmic scale - one tenth of a Bel.

7. **Earplug**: A personal hearing protection device that is worn inside the external ear canal (aural) or in the concha against the entrance to the external ear canal (semi-aural).

8. **Earmuff**: A personal hearing protection device which is worn over the ears and is comprised of a head band and ear cups with a soft outer ring intended to fit tightly against the pinna (supra-aural) or the side of the head around the pinna (circumaural).

9. **Permanent threshold shift (PTS)**: A permanent increase of the threshold of audibility for an ear at a specified frequency above previously established reference level.

10. **Personal hearing protector**: A device that is worn to prevent the effects of harmful noise exposure to the auditory system.
11. Probe microphone measurement: An instrument which allows the measurement of sound at the tympanic membrane.

12. Real-ear measurement: A test in which one relies on the subject's response to information presented to the ear.

13. Real-ear protection at threshold: The mean value (in decibels) of the occluded threshold (hearing protection in place) of audibility minus the open threshold of audibility (ears open and uncovered) for all listeners on all trials under otherwise identical test conditions.

14. Sensitivity: Biological variation of an individual's reaction to noise.

15. Sound pressure: Fluctuations in air pressure caused by a vibrating body.

16. Temporary threshold shift (TTS): Temporary hearing loss incurred as the result of noise exposure, all or part of which is recovered in an arbitrary period of time during the absence of noise exposure.

17. Threshold: The lowest level of sound consistently heard by the individual being tested.
REVIEW OF LITERATURE

Introduction

We live in an increasingly noisy world, in which protection of human hearing is an urgent need. A very common form of such protection is the personal hearing protection device (PHPD) (Rico & Alberti, 1982; Miller, 1986; Sataloff & Sataloff, 1987).

If the PHPD is to be most efficient, we must improve knowledge of how best to measure PHPD efficiency and of how best the device should be worn and cared-for. The following discussion is a review of significant literature describing and evaluating current methods for determining the attenuation afforded by PHPD's. Numerous methods have been proposed for measuring the noise reduction capabilities of personal hearing protection devices, but none of these methods has been universally accepted (Berger, 1986).

Methods for evaluating the noise reduction capabilities of the PHPD are either subjective or objective procedures. The subjective evaluation relies on the perceptive judgement of the subject to auditory stimuli presented under occluded and unoccluded conditions, earplugs in place opposed to no earplugs in the ears. The difference between the subject's response during occluded and unoccluded conditions will
determine the attenuation afforded by the device.

The only accepted protocol for testing the attenuation factors of PHPD's is the subjective method described by the American National Standards Institute (ANSI), ANSI-S3.19-1974 (Sataloff & Sataloff, 1987), a subjective, real-ear, psychoacoustic evaluation of (PHPDs). In this method, the attenuation obtained by the device is a perceived threshold shift determined by a non-occluded pure tone test.

The selected devices are then placed in both ears and the non-test ear is covered with an earmuff type protector to further prevent the test stimuli from penetrating the non-test ear. The subject is positioned at 90° azimuth and a pure tone test is re-administered (see Figure 1). Subtracting unoccluded ear threshold levels from the occluded ear's threshold, gives the attenuation factor of the device. In this test, the subject must respond by raising a hand or pressing a button when he/she believes a sound was heard.

In contrast, the test protocol of the probe microphone measurement instrument does not require a response from the subject. Rather the probe microphone method gives information on the reduction of a given volume of sound presented outside the ear when the sound is measured inside the ear behind the hearing protection device. Objective evaluations also depend on the difference between two measurements, though the data are the result of measurements collected by instrumentation and not from a response of a
FIGURE 1. Subjects were placed in an IAC sound isolation room and with a narrow band noise presented at 90° azimuth to the test ear in a diffuse sound field. The data are collected by a transducer located in or near an artificial or real ear.

Personal Hearing Protection Devices

Guidelines of the Occupational Safety and Health Association require that industrial noise be controlled at the source of generation if possible. When engineering
controls are not possible, the employer must require
employees to use personal hearing protection devices if they
are subjected to significant levels of noise exposure (85dB
for an eight hour exposure).

Two basic types of hearing protection devices are
available--insert plugs and ear muffs. The insert plug can
be pre-molded, formable, and custom molded. The ear muffs
come in several shapes and sizes and can be worn over the
head or attached to the side of safety helmets.

Alberti, Abel, and Riko (1982) had three criticisms of
personal hearing protection devices. First, it is difficult
to produce an effective noise barrier, especially if
multiple protectors are worn; second, discomfort is
associated with wearing the device; and third, the device
can limit communication.

Limitations of PHPD's are well defined (Rico & Alberti,
1981; Alberti, Abel, & Rico, 1982; Lempert & Edwards, 1983;
Savell & Toothman, 1987; Sataloff & Sataloff, 1987).
Particular problems include: (a) earmuffs attached to a hard
hat--the pressure of the seals on the head is often less
than that if the muff is worn on a spring band; (b) safety
glass temples could interfere with the ability of the muff
to seal between the earmuff and the side of the user's head;
(c) uncomfortable devices increase reluctance to wear the
device. If the device is not worn as it was designed, its
effectiveness is lessened or nullified. Noise will continue
to reach the cochlea causing irreparable physiological
damage (Lempert & Edwards, 1983).

In a study of 1,250 factory workers, Riko and Alberti (1982) examined hearing protectors for integrity against noise and adequacy of fit. Some workers were unable to adequately fit the protection devices while other workers had never been instructed how to wear the protectors and were using inappropriate fitting techniques. The most common problem found was a lack of understanding of how devices should be fitted. Several workers complained of discomfort as the main reason for not wearing devices. Workers were found with objects such as pencils placed between the earmuffs and the side of the head for reasons such as "my ears were getting hot." Workers with foam plugs were found to be wearing the plugs with very little of the plug in the canal because "they (the plugs) were more comfortable and easier to put in and out." Some insert-type plugs were worn a size too small due to increased comfort. Major problems were found to occur from a combination of poor instruction, poor supervision and poor employee motivation. Better employee training and supervision was suggested to assist in increasing motivation for wearing the devices.

Lempert and Edwards (1983) reported on a study of noise reduction afforded by insert-type protection devices. Using the ANSI standard S3.19-1974 method for measuring real-ear protection, the authors evaluated 420 subjects in 15 different plants. The criteria used in selecting subjects
included hearing level not greater than 40dB at any frequency in at least one ear and a difference of left and right ear hearing levels not greater than 20dB at more than one frequency. After the workers were tested five times over a two week period, they were relieved from the work situation and shown a sign "It is time for your hearing test - Do not touch your earplugs." The subject was then given the sign to hold with both hands and escorted to the test van. The first test was with the ears occluded, after which a second test was given with the ear plugs removed. This process was repeated five times for each subject. Results of the Lempert-Edwards study indicated a statistically significant difference between the attenuation received in the first field test of all workers and in the four subsequent tests. Although extreme care was taken to assure that the workers would not know when they would be tested, it was believed that because they did know they eventually would be tested there was incentive to fit the earplugs more effectively during the second through fifth tests. It was concluded that for any given earplug design, there may well be a large difference between attenuation values established in the laboratory and those measured in an industrial setting. The authors recommended that more time be spent in educating and monitoring employees on proper use of their personal hearing protection devices.

Adequate fitting of hearing protection is only one issue of apparent concern in the literature on hearing
protection devices. The actual attenuation factor of hearing protection devices is also the subject of several important studies. Royster, Royster and Cecich (1984) compared the Sieke Norton Comfit ear plug, Flents Silenta Model 1080 earmuff and E.A.R. foam ear plugs in an industrial facility of 150 workers. The facility's noise levels had a time-weighted average of 107dB. Four annual audiograms were evaluated to determine mean values of percent BWs statistic (sequential percent better or worse). The results indicated that the percent BWs statistic for properly protected population with past audiometric test will be less than 30 percent. The E.A.R. group showed an acceptable percent BWs value (26%) but the Silenta wearers (45%) and Comfit wearers (53%) showed excess variability in threshold measurements from year to year.

In contrast to the aforementioned study, Savell and Toothman (1987) reviewed audiograms of 265 employees in a facility with (OSHA) noise levels of 86 to 103dB. PHPD's were used by all employees to determine if the group means of hearing threshold levels were differed from the same group means developed eight years earlier. The group means data were essentially no different over the eight year period for those employees using personal hearing protection devices while exposed to hazardous work place noise levels. These results were proposed as a standard to indicate an effective hearing conservation program (DHEW/NIOSH publication number HSM73-11001, 1972).
Subjective Test of Real Ear Attenuation of Personal Hearing Protection Devices

Real ear attenuation at threshold is the oldest and most common method for measuring noise reduction by personal hearing protection devices. Binaural hearing thresholds are determined with ears non-occluded (Watson, & Knudsen, 1944). The PHPD is then inserted into the ear canal, and hearing thresholds are re-measured, the results being considered to be the occluded thresholds. The difference between the non-occluded thresholds and the occluded thresholds is a measure of the attenuation afforded by the device being tested.

Berger (1986), proposed several considerations that must be addressed to ensure data accuracy when using the real-ear attenuation at threshold method for measuring the attenuation afforded by personal hearing protection devices. According to Berger, ambient noise, stimulus presentation, frequency range, and physiological noise are vital areas of concern in obtaining accurate data in hearing protection attenuation experiments.

Ambient Noise

When experiments with the attenuation of hearing protection devices are conducted the test room must be "sufficiently quiet" (American National Standards
Institute's "Criteria for Permissable Ambient Noise During Audiometric Testing," ANSI S3.1-1977). High ambient noise levels in the test area will, in effect, mask the open ear thresholds, resulting in elevated open-ear thresholds. The occluded thresholds will less likely be affected, reducing the overall threshold shift and resulting in lower measured attenuation values.

Waugh (1970) demonstrated the masking effect of background noise with two different ear muffs. He suggested a background noise criterion based on a comparison of the non-occluded hearing threshold levels of the human test subject to that of normative data. Waugh determined the levels of broad-band background noise required to mask low frequency non-occluded ear threshold levels by 0, 3.5, 7.5, and 11.5 dB., averaged across eleven (11) test frequencies from 100-1000 Hz.

Berger and Kerivan (1981), presented a statistical analysis to verify Waugh's data. The basis of Berger's analysis was the 1/3 octave band diffuse-field threshold data from Berger (1981), combined with Hawkins and Stevens (1950), data on the ratio in dB between the masked threshold of a pure tone and the pressure spectrum level of a uniform masking level presented at the same frequency, i.e., the critical ratio. Berger checked Waugh's data by predicting the amount of masking that should have been created by the sound levels reported. For the test frequencies of 125, 250, 500, and 1000 Hz, the predictions for the 3.5-dB masker
were within 0.3, 0.6, 0.3, and 1.5 dB, respectively, and for the 11.5 dB masker the agreement was within 1.4, 1.1, 0.6, and 0.8 dB, respectively as that which had been reported by Waugh. Berger concluded that this procedure would provide a higher degree of accuracy in predicting the effect of masking with non-occluded testing as well as affording further support to Waugh's concern of ambient noise levels during non-occluded data collection.

Stimulus Presentation

The earliest real-ear-attenuation-at-threshold-test (REAT) standard was the ANSI Z24.22-1957 (ANSI, 1957). This standard specified the use of pure tone stimuli, presented to a test subject in an anechoic chamber at frontal positioning. Because of the acoustical environment, measurements of this type can easily be perturbed by small movements of the test subject.

Another potential problem with the use of pure tones as stimuli for measuring the attenuation at threshold of hearing protection devices is that the attenuation may vary because of resonances of PHPD's with small changes in frequencies above 500Hz (Berger, 1986). Berger concluded that pure tone attenuation measured at octave band center frequencies may not provide accurate noise reduction data for the device being evaluated.

Webster et al. (1956), compared real ear attenuation at
threshold for pure tone, 1/2 octave band and 1/1 octave band stimuli. The use of bands of noise or pure tones yielded results that were "roughly equivalent." Waugh (1974), compared real-ear attenuation at threshold results using pure tone and 1/3 octave band stimuli in their studies of attenuation characteristics of hearing protection devices. This study reported no significant difference in data collected using either test stimulus, conclusions were similar to those provided by Webster et al., providing an even closer agreement between the two stimuli.

Physiological Noise

Berger (1986), regarded the problems occurring with the occlusion effect when personal hearing protection devices are tested with real-ear attenuation at threshold test. Anderson and Whitle (1971), defined the occlusion effect as a "low frequency noise phenomenon (below 1000Hz.) which is vascular and/or muscular in nature." When the ear is occluded physiological noise is amplified. Huizing (1960), saw that the occlusion effect is a phenomenon of enhancement of the outer ear bone conduction pathway when the ear canal is occluded by an insert hearing protection device or covered with an ear muff. Low frequency acoustical energy is generated by canal wall vibrations and will then radiate and couple to the ear drum. Once the eardrum is set into motion, regardless of the mechanism causing the vibration,
the acoustical energy is transmitted along ossicles to the cochlea as if it were a normal external acoustical signal. The occlusion effect, primarily at low frequencies, is less as frequency increases, and has virtually no effect beyond 2000 Hz. (Killion, 1978). Berger concluded that amplified physiological noise or head noise, will mask occluded ear thresholds at low frequencies. The masking effect can create an elevation of thresholds by as much as 4-11 dB., at 125 Hz. and 1-10 dB. at 250 Hz. (Villchur, 1972) though the lower estimates are more reliable (Schroeter & Poesselt, 1984).

Berger and Kerivan (1983) found that the amount by which real-ear attenuation at threshold data were amplified depended on the volume of the occluded ear. They concluded that real-ear attenuation at threshold evaluation of hearing protection devices would produce data representative of the attenuation that the device would actually afford. Given the areas of concern suggested by Berger, it is evident that to ensure accurate data collection, great care must be taken when using the subjective real-ear method of determining attenuation factors of personal hearing protection devices.

Objective Test of Real-Ear Attenuation of Personal Hearing Protection Devices

The objective test to determine threshold attenuation data of personal hearing protection devices offers another
method of evaluating the noise reduction the devices will afford. There are three methods of collecting data in the objective test (Berger, 1986). The first is by use of an artificial head test fixture, the second is with a microphone in the real ear, and the third is with a microphone in the ear of a cadaver.

Probe Microphone in the Real Ear

The use of a microphone in a real ear is one method of testing the effectiveness of a personal hearing protection device with the advantage of better—or possibly more accurate test results. By using a real ear, the devices are tested with the same problems faced when the device is placed in the ears of users in real world conditions (Berger, 1986).

Researchers began to investigate the use of the microphone in the real ear by the mid-1950's (Webster, 1955). Many research articles have been published since that time involving real-ear microphone testing. The review of this paper will be limited to only research articles which involve the use of real-ear test methods and probe microphone testing in the use of monitoring the attenuation factors of personal hearing protection devices.

Weinreb and Touger (1960) found close agreement between data collected with real-ear microphone objective test methods and those of real-ear subjective test methods.
Throughout the frequencies tested the subjective test was found to be three to five dB higher than data obtained by the objective method except at a test frequency of 2000 Hz. where test results were lower, presumably the result of the occlusion effect. As the attenuation of the hearing protection device approaches bone conduction levels, it is deemed likely that lower scores will result at the test frequency of 2000 Hz., a phenomenon not unexpected since bone conduction is most sensitive at 2000Hz.

Weinreb and Touger (1960) concluded that real-ear attenuation threshold values are limited by the attenuation of the protection device especially at 2000 Hz. The authors also stated that data variability was no smaller for the objective test from the subjective test, suggesting that the primary variability is in the placement of the device and not in the difference of the two test paradigms.

Brammer and Piercy (1977) devised a technique for monitoring sound pressure in the ear. To measure the change in sound pressure with microphone position, a male test subject was seated in an anechoic chamber 1.5 meters from the loudspeaker which was positioned at ear level directly in front of the test subject. When data were obtained by using a pink noise and a 1/3 octave band noise, pressure transformation was independent of position of the microphone at frequencies below 6000 Hz. The authors concluded that this technique for monitoring sound pressure in the external ear canal is particularly suited for studies involving noise
exposure.

Schroeter (1986) reviewed past research comparing subjective and objective testing methods in support for his study of the use of test fixtures (artificial heads) for measuring REAT factors. He concluded that data collected in these previous studies confirm the doubts of accuracy of REAT method for testing protection devices. Schroeter used this data to support the use of artificial head test fixtures as a more reliable method of measuring attenuation factors afforded by PHPD's.

Schroeter (1986) also reviewed a study by Berger and Kerivan (1983), which examined the REAT method of testing the insertion loss of insert, semi-aural, supra-aural, and circumaural PHPDs. Results of this study were compared with results of a study using a canal-mounted subminiature microphone to measure the attenuation afforded by personal hearing protection devices.

Berger and Kerivan (1983) used six different types of personal hearing protection devices, on six subjects. Each subject had a subminiature microphone mounted in the left ear 10 to 14 mm into the external auditory meatus for all personal hearing protection devices. The only exception to this measurement was the E.A.R. insert plug, where the microphone was mounted 2 to 3 mm from the tympanic membrane. The experimental procedure consisted of conducting a monaural REAT test and a monaural insertion loss test for each fitting of the PHPD’s used in this study, with two
replications per device on each subject. Berger and Kerivan concluded that the REAT method will yield data representative of the attenuation that the insert type personal hearing protectors will produce in frequencies of 125 to 2000 Hz. However, in the lower frequencies (125 and 250 Hz) the REAT values for semi-aural, supra-aural, and low volume circumaural devices may be spuriously high by as much as 5 dB, due to masking of occluded thresholds by physiological noise. For insert devices and medium-to-large volume earmuffs the overestimation will be closer to zero. The difference is obtained by comparing data collected from REAT method with that data which was collected using the subminiature microphone test method.

**Probe Tube Microphone Test**

**REAT Mean Attenuation in dB SPL**
Was Compared with Those Obtained from Two Probe Tube Conditions

Traynor, Ackley, and Wiersbowski (1989) tested normal hearing patient population seen for audiological services (N = 25 subjects) with the REAT (RE) test method to determine the real ear threshold attenuation of the Norton Decidamp formable plug and the Triple Flange plug (issued to U.S. Army personnel), hearing protection devices.

Insertion held condition (IH) was conducted using the Madsen IGO-1000. The probe tube was placed a measured
distance into the external auditory meatus, and the canal resonance (external ear transfer function) was obtained.
The PHPD was inserted into the canal holding the probe tube in place, and the protection device was held in place with the finger to increase the hermetic seal afforded by the PHPD. The canal resonance measurement was taken again. A third measurement, insertion condition (I) was taken. This condition was produced with the same methods as the HI condition only the PHPD was not held in place.

Traynor et al. reported the RE condition attenuation results were most average in all test subjects. It was stated that the goal of this study was to determine how close the IH and/or the I measurement techniques were to the RE measurement. The results indicated the IH condition was the closest to the RE data for both hearing protection devices used. The differences between the IH and I methods was thought to be due to a loss of hermetic seal due to the insertion of the probe tube between the PHPD and the ear canal. It was stated that closer average attenuation measurement could have been obtained by allowing the probe tube to be put through the center of the PHPD, allowing a better hermetic seal.

It was concluded that this provided data which would support the suggestion of a statistically predictable trend in the average attenuation in dB SPL measured by probe tube microphone systems when compared to the REAT measurement. It was stated that one could estimate REAT measured average
attenuation in dB SPL afforded by PHPDs by utilizing probe tube microphone measurements. The data from this study suggested one could add 17.94 dB to the average insertion measurement within the frequencies of 500-4000 Hz to estimate the REAT within the same frequency spectrum for the Norton Decidamp PHPD. Similarly, by adding 16.44 dB to the average insertion measurements for the frequency range of 500-4000 Hz would provide an estimated REAT for the Triple Flange PHPD.

Gerling, Metz, Roemer-Bonko, and Rowsey (1989) conducted a similar study to that of Traynor et al. (1989). The Gerling et al. study used a prototype split microphone probe tube assembly which was designed specifically for obtaining REAT measures.

This study obtained REAT data from 12 normal hearing adults aged 21 through 41 years. Subjects were students, staff and faculty in the audiology program at Cleveland State University and were experienced with audiometric protocol.

The data was obtained using a probe tube measurement device with a split microphone unit with the probe tube fit through the center of an E.A.R. foam plug PHPD. The plug was then placed into the subject's ear. Real ear measures were made at 85 and 95 dB SPL. These levels were chosen to best simulate the high intensity noise levels experienced in the work environment. This would allow the opportunity to evaluate the linearity of attenuation of the EAR plug.
Following the objective test each subject was given a subjective evaluation or REAT measurement with the E.A.R. PHPD.

The recorded data from both test methods shows the objective test data scores to be considerably lower than the data obtained by the subjective test method. Though test-retest reliability was very consistent with that of the objective test mode showing differences of not greater than 2 dB variation in the mean data for each frequency.

Gerling et al. concluded by suggesting that probe tube microphone testing shows promise for the future, in providing a standardized test method for measuring the attenuation provided by personal hearing protection devices.

Summary and Conclusions from the Literature

The REAT method for testing personal hearing protection devices will not provide data which correlate with those obtained using the real-ear microphone method. The literature further suggests that the most likely variances in the data will be in test frequencies of 250 and 500Hz, a critical area because hearing protection devices provide the least protection in these areas. Berger (1984) and Berger and Kerivan (1983) considered the occlusion effect to be the major factor for lower scores developed by the REAT method of testing.

The commercial probe microphone test instrument might
offer a new and possibly better method for measuring efficiency of hearing protectors than the presently accepted ANSI standard. The study reported in this thesis provides a comparison of these two test methods for measuring attenuation factors of PHPD's.
PROCEDURES

Nature of Subjects and Personal Hearing Protection

Fifteen subjects (30 ears) were selected from volunteers living in the Eugene area. To qualify as a subject, the person had to be at least 18 years old with hearing threshold levels less than or equal to 15 dB throughout all test frequencies. Further requirements included no known history of hearing loss, no previous use of personal hearing protection devices, and no history of extreme noise exposure.

Each subject was first given an otoscopic evaluation by a graduate student in Audiology, to insure that the canal was clear of disease or of an overabundance of cerumen. Any subject proving to have external auditory meatus-related problems was released from this study and appropriate medical referral was made. One volunteer was released from the study for medical referral.

Seven females and eight males, (n=30 ears) were subjects for this experiment. All subjects participated in both the subjective and objective methods of measuring the noise attenuation of PHPDs. All subjects were Caucasian, of ages ranging from 19 through 41 (Appendix A). Hearing threshold levels on all test subjects were within normal

Nature of Techniques of Fitting

The personal hearing protection device fitting technique required both the experimenter and subject working together attempting to achieve an optimum fit. If the subject felt that the device was not fitting tightly, a further attempt would be made to fit the device correctly. Best fit possible was required because this experiment utilized two testing procedures and optimum fitting was required to evaluate both methods evenly.

Test Instruments

The personal hearing protection devices used in this study were the E.A.R. foam insert, the 3M AttenuTech 6300 foam insert, and the MAX preshaped foam insert. The Pelte H-9 ear muff hearing protector was used to cover the hearing protection in the non-test ear. Manufacturer's published specifications for the devices used in this study are shown in Tables 1 through 4.

Equipment

The instrumentation used in this study to accumulate
<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>E.A.R. Foam Insert</th>
<th>3M Attenutech 6300 Foam</th>
<th>MAX Preshaped Foam Insert</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>125 250 500 1000 2000 3150 4000 6300</td>
<td>125 250 500 1000 2000 3150 4000 6300</td>
<td>125 250 500 1000 2000 3150 4000 6300</td>
</tr>
<tr>
<td>Real-ear Attenuation</td>
<td>33.4 35.7 37.6 40.3 41.8 44.3 45.8 46.1</td>
<td>32.6 38.0 40.6 38.4 38.1 42.1 42.9 46.3</td>
<td>32.3 34.5 38.1 38.3 38.4 42.8 44.5 45.2</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>2.1 1.7 2.0 1.7 2.1 1.9 1.7 2.1</td>
<td>6.1 8.0 6.2 4.4 2.4 3.6 3.8 4.5</td>
<td>5.0 4.3 3.6 3.1 2.7 3.8 4.3 4.8</td>
</tr>
</tbody>
</table>

**Noise Reduction Rating**
- **E.A.R. Foam Insert**: 35 decibels
- **3M Attenutech 6300 Foam**: 29 decibels
- **MAX Preshaped Foam Insert**: 33 decibels
TABLE 4. Peltor H-9 Ear Muff Hearing Protection Device

<table>
<thead>
<tr>
<th>Manufacturer's specifications</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>3150</th>
<th>4000</th>
<th>6300</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency (Hz)</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Real-ear Attenuation</strong></td>
<td>13.4</td>
<td>16.4</td>
<td>24.7</td>
<td>32.4</td>
<td>37.5</td>
<td>39.3</td>
<td>38.5</td>
<td>35.2</td>
</tr>
<tr>
<td><strong>Standard Deviation</strong></td>
<td>1.4</td>
<td>2.7</td>
<td>2.2</td>
<td>2.0</td>
<td>2.3</td>
<td>1.9</td>
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<td><strong>Noise Reduction Rating</strong></td>
<td></td>
<td></td>
<td></td>
<td>22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Test data included:

1. Glaser R-100 audiometer, calibrated to ANSI S3.6-1969 (R1973) specifications. Tone test frequencies were 250, 500, 750, 1000, 1500, 2000, 3000, 4000, 6000 Hz.

2. Frye Electronics Fonix FP30 Portable Real Ear/Probe Microphone Analyzer with FM12 microphone, calibrated to ANSI S3.22-1982 specifications. Tone test frequencies at 1/6 octave frequencies were from 250 - 6300 Hz.


Condition No. 1 Subjective Test Method

To fully examine the hypothesis involving the use of the subjective test method for measuring the attenuation values of personal hearing protection devices, three types
of canal insert hearing protection devices were used. These devices are described in Tables 1, 2, 3.

The study began with the establishment of hearing threshold levels. The subject was placed in a I.A.C. 402 single wall sound chamber then an E.A.R. foam insert hearing protection device was placed in the left ear covered by a Peltron H-9 ear muff hearing protection device. This precaution was taken to insure that the left ear would not be involved in the test of threshold values of the right ear. The subject was placed in a chair and positioned with the right ear at 90° azimuth and one meter from the loudspeaker (see Figure 1). Hearing threshold measurements were obtained by presenting a narrow-band noise (+1dB, 250 - 6000Hz.) in a diffuse sound field, subjects responded by raising a hand to indicate the sound was heard.

Upon completion of the right ear thresholds the left ear was cleared of the hearing protection devices and the right ear was then fitted with an E.A.R. insert hearing protection device. Procedure was followed as described for the left ear. E.A.R. insert hearing protection devices were used to isolate opposite ear in threshold testing because such devices had the highest NRR (E.P.A. NRR = 36dB).

The subjects who met the experiment qualifications were then called for data collection. Test procedures for each subject were:

1. The test subject was placed in the test chamber, E.A.R. insert hearing protection plugs were inserted, and
the subject was allowed to rest for three to five minutes to allow the foam plugs to fully accommodate the ear canal before testing began. The Pelter H-9 ear muff hearing protection device was placed over the non-test ear. The subject was placed in a chair and positioned with the right ear at 90° azimuth and one meter from the loud speaker (see Figure 1). Hearing threshold measurements were obtained by presenting a narrow-band noise (+1 dB, 250 - 6000 Hz.) in a diffuse sound field.

2. The subject traced his diffuse sound field threshold shift for the E.A.R. hearing protection device in the right ear.

3. The subject was repositioned with the left ear at 90° azimuth and one meter from the loudspeaker (see Figure 1), and the Pelter H-9 ear muff hearing protection device was placed over the non-test ear. Hearing threshold measurements were obtained by presenting a narrow band noise (+1 dB, 250 - 6000 Hz.) in a diffuse sound field.

4. The Hearing protection devices were removed and the subject was rested for five minutes.

Test steps (a) - (d) were repeated for the 3M-6300 and the MAX insert hearing protection devices. The order of testing the three types of hearing protection devices was randomized across test subjects.
Condition No. 2 Objective Test Method

In order to effectively examine the objective test method for measuring the attenuation values of personal hearing protection devices, three types of canal insert hearing protection devices were utilized. These devices are described in Tables 1, 2, and 3. The hearing protection devices required slight modification to be used with the Frye Electronics 3300P real ear analyzer. Each insert hearing protection device was reamed through the center with a three millimeter surgical bore, for the placement of the microphone probe tube. The probe microphone tube was inserted and glued into place. The test procedures for each subject were as follows.

1. The test subject was placed in the test room and positioned with the right ear at 90° azimuth and one meter from the loud speaker (see Figure 1). An E.A.R. insert hearing protection device with the probe tube was inserted and the subject rested for three to five minutes to allow the foam plugs to fully accommodate to the ear canal before testing began. The shield was placed over the probe microphone tube, modeling clay (fun tac) was used to seal the probe microphone tube within the shield, (see Figure 2), and the probe tube was then connected to the microphone.

The test was then initiated. The Frye Electronics FP30 real-ear analyzer was preset to measure acoustic gain, the instrument was started and measurements were recorded.
2. The hearing protection devices were removed and the subject was given five minutes to rest.

3. The test subject was positioned with the left ear at 90° azimuth and one meter from the loud speaker and the same set up procedures were used as were described for right ear testing. The test was then initiated. The Frye Electronics FP30 real-ear analyzer was preset to measure acoustic gain, the instrument was started and measurements were recorded.

The test steps a - c were repeated for the 3M-6300 and the MAX insert hearing protection devices. The order of testing the three types of hearing protection devices was randomized across all test subjects.
Statistical Analysis

Mean and standard deviations were used to analyze the data and formulate responses to the experimental questions. Means of test data with standard deviations for both subjective and objective test methods were plotted into graph format and test result differences were compared using correlated $t$-tests ($p < .001$), to determine whether there were any statistical differences between the real-ear method of measurement and the probe microphone measurements for each hearing protection device. For the purpose of this study, the level of confidence for significant differences will be set at $p < .001$. Mean data were also compared using the MANOVA for repeated measures method to review results of the two methods of measurement to determine whether there were any statistical differences between the two test methods.
ANALYSIS AND INTERPRETATION OF DATA

The data were analyzed with a Digital Equipment Company VAX/VMS-V50-2 computer, located at the University of Oregon. The Standard Statistical Package for the Social Science (SPSS-X) release 3.1 was used to perform t-test and MANOVA procedures on data collected for this study.

Correlated t-tests (p < .001) were used to determine differences between sample mean (experiment data) and population mean (manufacturer's specifications) of the three hearing protection devices used in this study. The MANOVA test for repeated measures was used to determine differences of subjective group mean attenuation levels of all three hearing protection devices with that of the objective group mean attenuation from levels of the same three types of hearing protection devices.

MANOVA

The MANOVA for repeated measures test was used to analyze the mean attenuation deviations from manufacturer's published specifications for the E.A.R., MAX, AND 3M PHPDs using the objective and subjective test methods. The results using this method of comparison indicate the six deviations to be significantly different (F .2476.10, df =
29, 1, \( p < .0001 \) (Table 5).

**TABLE 5.** MANOVA Data Results for Differences Between Mean Attenuation Levels for the Objective and Subjective Test Methods

<table>
<thead>
<tr>
<th>MANOVA</th>
<th>SS</th>
<th>DF</th>
<th>MS</th>
<th>F</th>
<th>SIG of F</th>
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<tr>
<td>Within Cells</td>
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<td>24.83</td>
<td>2476.10</td>
<td>.0001</td>
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<tr>
<td>Constant</td>
<td>59495.90</td>
<td>1</td>
<td>59495.90</td>
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</tbody>
</table>

Data for mean, variance, and standard deviations for all frequencies tested using the 3M 6300, E.A.R., and the MAX PHPDs can be found in Appendix C.

Results for the E.A.R. Brand Hearing Protection Device

The results of the correlated \( t \)-test with a confidence level of (\( p < .001 \)) indicate that mean attenuation scores for the E.A.R. PHPD using the objective test method, deviated significantly more from the manufacturer's published mean attenuation specifications than did the E.A.R. PHPD using the subjective test method (\( t = -17.23, \ 29, \ p < .0001 \)), indicating the range of attenuation was higher for the subjective test method than that obtained from the objective test method (Table 6). Levels of attenuation do not appear to be linear between test methods.
TABLE 6. Correlated t-Test Results for Differences Between Mean Attenuation Levels for the E.A.R. PHPD, Using Objective and Subjective Test Methods

<table>
<thead>
<tr>
<th>variable</th>
<th>number of cases</th>
<th>mean</th>
<th>standard deviation</th>
<th>standard error</th>
<th>difference mean</th>
<th>standard deviation</th>
<th>standard error</th>
<th>2-tail corr. prob.</th>
<th>cor. prob.</th>
<th>2-tail prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>EAR OB</td>
<td>30</td>
<td>8.0657</td>
<td>3.877</td>
<td>1.073</td>
<td>20.4000</td>
<td>8.486</td>
<td>1.104</td>
<td>.124</td>
<td>.514</td>
<td>17.23</td>
</tr>
<tr>
<td>EAR SB</td>
<td>30</td>
<td>28.4657</td>
<td>3.567</td>
<td>.651</td>
<td>11.184</td>
<td>1.161</td>
<td>.127</td>
<td>9.64</td>
<td>.0001</td>
<td></td>
</tr>
</tbody>
</table>

Results for the MAX Brand Hearing Protection Device

The results of the correlated t-test with a confidence level of (p < .001) indicate that mean attenuation scores for the MAX PHPD using the objective test method, deviated significantly more from the manufacturer's published mean attenuation specifications than did the MAX PHPD using the subjective test method (t = 9.64, 29, p < .0001), indicating the range of attenuation was higher for the subjective test method than that obtained from the objective test method (Table 7). Levels of attenuation do not appear to be linear between test methods.

TABLE 7. Correlated t-Test Results for Differences Between Mean Attenuation Levels for the MAX PHPD, Using Objective and Subjective Test Methods

<table>
<thead>
<tr>
<th>variable</th>
<th>number of cases</th>
<th>mean</th>
<th>standard deviation</th>
<th>standard error</th>
<th>difference mean</th>
<th>standard deviation</th>
<th>standard error</th>
<th>2-tail corr. prob.</th>
<th>cor. prob.</th>
<th>2-tail prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAX OB</td>
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<td>10.4662</td>
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<td>1.158</td>
<td>15.4593</td>
<td>8.782</td>
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<td>.390</td>
<td>.033</td>
<td>9.64</td>
</tr>
<tr>
<td>MAX SB</td>
<td>30</td>
<td>29.9225</td>
<td>4.084</td>
<td>.746</td>
<td>15.4593</td>
<td>8.782</td>
<td>1.003</td>
<td>.390</td>
<td>.033</td>
<td>9.64</td>
</tr>
</tbody>
</table>
Results for the 3M Brand
Hearing Protection Device

The results of the correlated $t$-test with a confidence level of ($p < .001$) indicate that mean attenuation scores for the 3M PHPD using the objective test method, deviated significantly more from the manufacturer's published mean attenuation specifications than did the 3M PHPD using the subjective test method ($t = 20.24$, 29, $p < .0001$), indicating the range of attenuation was higher for the subjective test method than that obtained from the objective test method (Table 8). Levels of attenuation do not appear to be linear between test methods.

TABLE 8. Correlated $t$-Test Results for Differences Between Mean Attenuation Levels for the 3M PHPD, Using Objective and Subjective Test Methods

<table>
<thead>
<tr>
<th>variable</th>
<th>number of cases</th>
<th>mean</th>
<th>standard deviation</th>
<th>standard error</th>
<th>difference mean</th>
<th>standard deviation</th>
<th>standard error</th>
<th>$t$ value</th>
<th>degrees of freedom</th>
<th>2-tail prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M OB</td>
<td>30</td>
<td>8.8176</td>
<td>5.013</td>
<td>.915</td>
<td>10.5278</td>
<td>5.014</td>
<td>.915</td>
<td>.317</td>
<td>29</td>
<td>.0001</td>
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Using the correlated $t$-test ($p < .001$), a comparison between the E.A.R. and MAX brands of PHPDs for differences of deviation of mean attenuation levels from the manufacturer's published specifications using the subjective test method

The $t$-test was used to compare the differences of
deviation of mean attenuation levels between the E.A.R. and the MAX PHPDs from the manufacturer's published specifications. The comparison between the E.A.R. and the MAX PHPDs revealed no significant differences in amount of deviation from the manufacturer's published specifications using the subjective test method ($t = 1.44, 29, p < .161$) (Table 9).

TABLE 9. Correlated t-Test Results for Differences Between Mean Attenuation Levels for MAX and E.A.R. PHPDs, Using the Subjective Test Method

<table>
<thead>
<tr>
<th>Variable</th>
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<th>Mean</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
<th>Difference Mean</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
<th>t-value</th>
<th>Degrees of Freedom</th>
<th>p-value</th>
<th>2-tail Prob.</th>
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</thead>
<tbody>
<tr>
<td>EAR SB</td>
<td>30</td>
<td>3.0657</td>
<td>5.877</td>
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<td></td>
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<td></td>
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Using the correlated $t$-test ($p < .001$), a comparison between the MAX and 3M brands of PHPDs for differences of deviation of mean attenuation levels from the manufacturer's published specifications using the subjective test method.

The $t$-test was used to compare the differences of deviation of mean attenuation levels between the MAX and the 3M PHPDs from the manufacturer's published specifications. The comparison between the MAX and the 3M PHPDs revealed no significant differences in amount of deviation from the manufacturer's published specifications using the subjective test method ($t = 1.42, 29, p < .165$) (Table 10).
Using the correlated t-test (p < .001), a comparison between the 3M and the E.A.R. brand PHPDs for differences of deviation of mean attenuation levels from manufacturer's published specifications using the subjective test method.

The t-test was used to compare the differences of deviation of mean attenuation levels between the 3M and E.A.R. PHPDs revealed no significant differences in amount of deviation from the manufacturer's published specifications using the subjective test method (t = .55, 29, p < .587) (Table 11).

### TABLE 10. Correlated t-Test Results for Differences Between Mean Attenuation Levels for MAX and 3M PHPDs, Using the Subjective Test Method

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>MAX SB</td>
<td>30</td>
<td>10.4662</td>
<td>6.343</td>
<td>1.138</td>
<td>1.0486</td>
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<td>.395</td>
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<td>.165</td>
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<tr>
<td>3M SB</td>
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<td>5.013</td>
<td>.915</td>
<td></td>
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</tr>
</tbody>
</table>

### TABLE 11. Correlated t-Test Results for Differences Between Mean Attenuation Levels for E.A.R. and 3M PHPDs, Using the Subjective Test Method

<table>
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<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>EAR SB</td>
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<td>5.877</td>
<td>1.073</td>
<td>1.3519</td>
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<tr>
<td>3M SB</td>
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<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
Using the correlated $t$-test ($p < .001$), a comparison between the E.A.R. and MAX brand PHPDs for differences of deviation of mean attenuation levels from the manufacturer's published specifications using the objective test method.

The $t$-test was used to compare differences of deviation of mean attenuation levels between the E.A.R. and MAX PHPDs from the manufacturer's published specifications. The comparison between the E.A.R. and MAX PHPDs revealed a significant difference of deviations of mean attenuation levels from that of the manufacturer's published specifications using the objective test method ($t = 2.81$, 29, $p < .009$) (Table 12).

**TABLE 12. Correlated $t$-Test Results for Differences Between Mean Attenuation Levels for MAX and E.A.R. PHPDs, Using the Objective Test Method**

<table>
<thead>
<tr>
<th>variable</th>
<th>number of cases</th>
<th>mean</th>
<th>standard deviation</th>
<th>standard error</th>
<th>difference mean</th>
<th>standard deviation</th>
<th>standard error</th>
<th>2-tail corr. prob.</th>
<th>$t$</th>
<th>degrees of freedom</th>
<th>2-tail prob.</th>
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<tbody>
<tr>
<td>MAX OB</td>
<td>30</td>
<td>25.9255</td>
<td>4.884</td>
<td>.746</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>2.5403</td>
<td>2.81</td>
</tr>
<tr>
<td>EAR OB</td>
<td>30</td>
<td>21.4657</td>
<td>3.567</td>
<td>.631</td>
<td>2.5403</td>
<td>4.943</td>
<td>.902</td>
<td>.171</td>
<td>.367</td>
<td>29</td>
<td>.009</td>
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</table>

Using the correlated $t$-test ($p < .001$), a comparison between the MAX and 3M brand of PHPDs for differences of deviation of mean attenuation levels from the manufacturer's published specifications using the objective test method.

The $t$-test was used to compare the differences of
deviation of mean attenuation levels between the MAX and 3M PHPDs from the manufacturer's published specifications. The comparison between the MAX and 3M PHPDs revealed no significant differences in amount of deviation from the manufacturer's published specifications using the objective test method ($t = 1.68, 29, p < .103$) (Table 13).

**TABLE 13. Correlated t-Test Results for Differences Between Mean Attenuation Levels for MAX and 3M PHPDs, Using the Objective Test Method**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Number of cases</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
<th>Difference Mean</th>
<th>Standard Deviation</th>
<th>Standard Error</th>
<th>2-Tail Cor. Prob.</th>
<th>$t$ Value</th>
<th>Degrees of Freedom</th>
<th>2-Tail Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M OB</td>
<td>30</td>
<td>27.3454</td>
<td>2.184</td>
<td>.581</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Using the correlated $t$-test ($p < .001$), a comparison between the 3M and E.A.R. brand PHPDs for differences of deviation of mean attenuation levels from the manufacturer's published specifications using the objective test method.

The $t$-test was used to compare the differences of deviation of mean attenuation levels between the 3M and E.A.R. PHPDs from the manufacturer's published specifications. The comparison between the 3M and E.A.R. PHPDs revealed no significant differences in amount of deviation from manufacturer's published specifications using the objective test method ($t = 1.34, 29, p < .190$) (Table 14).
TABLE 14. Correlated t-Test Results for Differences Between Mean Attenuation Levels for E.A.R. and 3M PHPDs, Using the Objective Test Method

<table>
<thead>
<tr>
<th>variable</th>
<th>number of cases</th>
<th>mean</th>
<th>standard deviation</th>
<th>standard error</th>
<th>difference mean</th>
<th>standard deviation</th>
<th>standard error</th>
<th>2-tail corr. prob.</th>
<th>t value</th>
<th>degrees of freedom</th>
<th>2-tail prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>EAR OB</td>
<td>30</td>
<td>28.4657</td>
<td>3.567</td>
<td>.651</td>
<td>1.1204</td>
<td>4.569</td>
<td>.834</td>
<td>.007</td>
<td>.646</td>
<td>1.34</td>
<td>29</td>
</tr>
<tr>
<td>3M OB</td>
<td>30</td>
<td>27.3454</td>
<td>3.184</td>
<td>.581</td>
<td>1.1204</td>
<td>4.569</td>
<td>.834</td>
<td>.007</td>
<td>.646</td>
<td>1.34</td>
<td>29</td>
</tr>
</tbody>
</table>

Using the correlated t-test (p < .001), a comparison of mean attenuation deviations from manufacturer's published specifications for the E.A.R., MAX, 3M PHPDs using the objective and subjective test methods.

The correlated t-test was used to compare the difference of deviation of mean attenuation levels between the three hearing protection devices using the objective and subjective test method. The results using this method of comparison indicate a significant differences in the amount of deviation from manufacturer's published specifications (t = 21.09, 29, p < .0001) (Table 15).

TABLE 15. Correlated t-Test Results for Differences Between Mean Attenuation Levels for the Objective and Subjective Test Methods

<table>
<thead>
<tr>
<th>variable</th>
<th>number of cases</th>
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<th>standard deviation</th>
<th>standard error</th>
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<th>standard error</th>
<th>2-tail corr. prob.</th>
<th>t value</th>
<th>degrees of freedom</th>
<th>2-tail prob.</th>
</tr>
</thead>
</table>
The effectiveness of the objective test method with a probe microphone instrument was compared with the subjective test method (ANSI S3.16-1974) by measuring the noise attenuation afforded by three different hearing protection devices. Following are the experimental questions asked and findings as a result of comparative testing.

Tests With E.A.R. Insert Earplug

Experimental Question No. 1: The ANSI S3.19-1974 method for the measurement of Real-Ear Protection of Hearing Protectors and Physical Attenuation of Earmuffs will show no difference from manufacture's EPA Noise Reduction Rating as Specified for the Insert Earplug.

Experimental Question No. 2: Using the ANSI S3.19-1974 protocol, the probe microphone measurement instrument will provide data which will show a difference to the manufacturer's EPA Noise Reduction Rating as specified for the E.A.R.

Findings: The subjective test method (ANSI, 1974) yielded consistently higher mean attenuation values than those obtained with the objective test method (probe microphone) (Figure 3), as compared to data from the manufacturer's specifications in all frequencies tested. The statistics for the data collected for this study is not significantly different from the mean attenuation scores published by the manufacturer of the E.A.R. hearing
FIGURE 3. Objective group mean attenuation data compared with Subjective group mean attenuation data for the E.A.R. PHPD.
protection device (Figures 4, 5).

Individuals test responses were compared against manufacture's specifications (Figures 6, 7). Differences in the graphic array suggest that the objective test method appears to have provided more consistent responses than did the subjective method. Standard deviations from group mean for each device ranged from 2.2 - 6.1 for the objective method and 5.3 - 9.2 for the subjective method (Figures 8, 9). Manufacturer's mean attenuation variances were not published preventing proper statistical analysis of these data.

Tests With MAX Insert Earplug

**Experimental Question No. 3:** The ANSI S3.19-1974 method for the measurement of Real-Ear Protection of Hearing Protectors and Physical Attenuation of Earmuffs will show no difference from manufacture's EPA Noise Reduction Rating as Specified for the MAX Insert Earplug.

**Experimental Question No. 4:** Using the ANSI S3.19-1974 protocol, the probe microphone measurement instrument will provide data which will show a difference to the manufacturer's EPA Noise Reduction Rating as specified for the MAX.

**Findings:** The subjective test method (ANSI, 1974) yielded consistency higher mean attenuation values than those obtained with the objective test method (probe
KEY:

- Manufacturer's Mean Attenuation Levels
- Subjective Mean Attenuation Levels

FIGURE 4. The subjective test method the group mean attenuation levels are compared with manufacturer's mean attenuation specifications using the E.A.R. PHPD.
FIGURE 5. The objective test method the group mean attenuation levels are compared with manufacturer's mean attenuation specifications using the E.A.R. PHPD.
FIGURE 6. Individual responses using the subjective test method for the E.A.R. PHPD.
FIGURE 7. Individual responses using the objective test method for the E.A.R. PHPD.
FIGURE 8. Subjective test method illustrating the standard deviation from group mean attenuation levels using the E.A.R. PHPD.
FIGURE 9. Objective test method illustrating the standard deviation from group mean attenuation levels using the E.A.R. PHPD.
microphone) (Figure 10), as compared to data from the manufacturer's specifications in all frequencies tested. The statistics for the data collected for this study were not significantly different from the mean attenuation scores published by the manufacturer of the MAX hearing protection device (Figures 11, 12).

Individuals test responses were compared against manufacturer's specifications (Figures 13, 14). Differences in the graphic array suggest that the objective test method appears to have provided more consistent responses than did the subjective method. Standard deviations from group mean for each device ranged from 2.2 - 9.1 for the objective method and 6.5 - 9.3 for the subjective method (Figures 15, 16). Manufacturer's mean attenuation variances were not published, preventing proper statistical analysis of these data.

Tests With 3M 6300 Insert Earplug

**Experimental Question No. 5:** The ANSI S3.19-1974 method for the measurement of Real-Ear Protection of Hearing Protectors and Physical Attenuation of Earmuffs will show no difference from manufacture's EPA Noise Reduction Rating as Specified for the 3M 6300 Insert Earplug.

**Experimental Question No. 6:** Using the ANSI S3.19-1974 protocol, the probe microphone measurement instrument will provide data which will show a difference to the
FIGURE 10. Objective group mean attenuation data compared with subjective group mean attenuation data for the MAX PHPD.
FIGURE 11. The subjective test method the group mean attenuation levels are compared with manufacturer's mean attenuation specifications using the MAX PHPD.
FIGURE 12. The objective test method the group mean attenuation levels are compared with manufacturer's mean attenuation specifications using the MAX PHPD.

KEY: ● Manufacturer's Mean Attenuation Levels
    ■ Objective Mean Attenuation Levels
FIGURE 13. Individual responses using the subjective test method for the MAX PHPD.
FIGURE 14. Individual responses using the objective test method for the MAX PHPD.
FIGURE 15. Subjective test method illustrating the standard deviation from group mean attenuation levels using the MAX PHPD.
FIGURE 16. Objective test method illustrating the standard deviation from group mean attenuation levels using the MAX PHPD.
manufacturer's EPA Noise Reduction Rating as specified for the 3M 6300 insert earplug.

Findings: The subjective test method (ANSI, 1974) yielded consistency higher mean attenuation values than those obtained with the objective test method (probe microphone) (Figure 17), as compared to data from the manufacturer's specification in all frequencies tested. The statistics for the data collected for this study was not significantly different from the mean attenuation scores published by the manufacturer of the 3M hearing protection device (Figure 18, 19).

Individual test responses were compared against manufacture's specifications (Figures 20, 21). Differences in the graphic array suggest that the objective test method provided more consistent responses than did the subjective method. Standard deviations from group mean for each device ranged from 1.5 - 6.8 for the objective method and 5.2 - 10.2 for the subjective method (Figures 22, 23). Manufacturer's mean attenuation variances were not published, preventing proper statistical analysis of these data.

Experimental Question No. 7: The mean of the test (x) (ANSI S3.19-1974) will not be significantly different from the mean of the test (Y) (Probe Microphone Measurement Instrument).

Review of group mean attenuation afforded by the three PHPD's from the two test methods, shows a significant
FIGURE 17. Objective group mean attenuation data compared with subjective group mean attenuation data for the 3M 6300 PHPD.
FIGURE 18. The subjective test method the group mean attenuation levels are compared with manufacturer's mean attenuation specifications using the 3M 6300 PHPD.
FIGURE 19. The objective test method the group mean attenuation levels are compared with manufacturer's mean attenuation specifications using the 3M 6300 PHPD.
FIGURE 20. Individual responses using the subjective test method for the 3M 6300 PHPD.
FIGURE 21. Individual responses using the objective test method for the 3M 6300 PHPD.
FIGURE 22. Subjective test method illustrating the standard deviation from group mean attenuation levels using the 3M 6300 PHPD.
FIGURE 23. Objective test method illustrating the standard deviation from group mean attenuation levels using the 3M 6300 PHPD.
difference of attenuation between the subjective method and the objective method (see Figures 3, 10, 17). The data provided by the MANOVA for repeated measures test revealed indeed there is a significant difference between the mean of test (X) (ANSI S3.19-1974 from test (Y) Probe Microphone Measurement Instrument).
SUMMARY AND RECOMMENDATIONS

This study determined and described differences in attenuation measurements of three PHPD's under two different test methods. Group mean attenuation levels were compared for objective and subjective test methods for all three hearing protection devices used in this study. The intent of this comparison was to determine the test method that would more closely correspond with the attenuation levels published in the manufacturer's specifications.

In agreement with Behar (1981), Abel, Alberti, and Rice (1981), Lempert and Edwards (1983), Berger (1986), Gerling, Metz, Roemer-Bonko, and Rowsey (1989), and Traynor, Ackley, and Wiersbosky (1989), the data presented in this study shows the subjective test method provides data which more closely represents the manufacturer's published specifications, than that of the data collected using the objective test method. This result was expected based on the review of these studies which used similar test parameters.

The studies presented by Gerling, Metz, Roemer-Bonko, and Rowsey (1989) and Traynor, Ackley, and Wiersbosky (1989) suggested several problems with the subjective test method (poor hermetic seal with probe tube inserted between anal wall and hearing protection device; sound penetrating...
through the probe tube wall; sound penetrating through the wall of the microphone protective casing) which explain the differences in the attenuation performance of the PHPDs between the two test methods. With the problems associated with the objective test method, it is not considered to be the test method of choice in monitoring attenuation capabilities of PHPDs. This study, however, provides a comparison between the two test methods which suggest that the objective test method may provide a better accuracy than the subjective test method. The objective test method provides data which seems to be more consistent amongst test subjects than the data collected from the subjective test method (see Figures 6, 7, 13, 14, 20, 21). This data is supported by similar findings discussed in two studies presented in the review of the literature (Traynor, Ackley, & Wiersbosky, 1989; Gerling, Metz, Roemer-Bonko, & Rowsey, 1989). Traynor et al. suggested that the data collected using the probe tube microphone system to be consistent enough among test subjects that a correction factor could be used to estimate the REAT attenuation factors for the hearing protection devices used in their study. This research study appears to provide data which supports the consistency of the repeatability of data using the probe microphone test method as reported by the Traynor et al. (1989) study.

The data presented in this study, combined with the studies reviewed, suggest the importance of continued
research using the probe tube measurement instrument for the study of attenuation capabilities of PHPDs. The need to find a simple, fast, repeatable, and more cost-effective method for monitoring PHPD's attenuation levels is an important task.

This author suggests further research be conducted to determine if a correction factor for data collected using the probe microphone instrument, can be determined for each hearing protection device being used in the industrial community. If this is feasible, it then seems possible that a standardized test could be developed using the probe microphone instrument. This would make the probe test microphone instrument a viable tool to ensure better fitting of proper attenuating hearing protection devices for the noise environment in which the employee is exposed.

According to the annual reports filed by the Occupational Health and Safety Administration, the amount of workman's compensation claims filed for noise-induced hearing loss is on the increase each year. This provides an indication that there is a serious problem with the present management of employees working in high noise environments. It is important for researchers to help in providing information that will better protect the worker from permanent noise-induced hearing loss acquired from over-exposure to potentially damaging noise levels in the work environment. It was the purpose of this study to help provide data that would continue in that direction.
Accomplishing the goal of providing a better method of monitoring attenuation levels of PHPD's, will help in reducing future workmen's compensation claims for noise-induced hearing loss. More importantly, it will ensure better hearing for those workers exposed to high levels of noise in their work environments throughout their working careers.

Future Research

This study should be replicated using like procedures and some hearing protection devices with an increased sample size. In addition, statistical analysis should be compared with manufacturers' collected raw data to better determine analysis of consistencies between test methods. This expanded statistical analysis would provide specific information as to whether the probe tube microphone test method indeed will provide more consistent test data than that data which is collected using the subjective test method. With this information this author believes a correction factor can indeed be established and a standardized test method could be introduced.


APPENDICES
APPENDIX A

AGE & SEX OF TEST SUBJECTS
USED FOR THIS STUDY

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APPENDIX B

INDUSTRIAL ACOUSTICS COMPANY (IAC)

SOUND ISOLATION ROOM MODEL 402

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<td>W L H</td>
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<td></td>
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**NOISE REDUCTION**

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*±3dB for instrument accuracy

**SOUND ABSORPTION**

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<th>1k</th>
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APPENDIX C

RAW DATA FOR THE E.A.R., MAX, AND 3M PHPDs,
COLLECTED USING SUBJECTIVE AND
OBJECTIVE TEST METHODS

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