Sound restoration hearing protection: Genesis of a standard test method

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ABSTRACT

It is known that exposure to high sound pressure levels can lead to permanent hearing loss; however, many workers, in mining as well as other occupational sectors, frequently receive hazardous noise exposures. The National Institute for Occupational Safety and Health (NIOSH) recommends using a criterion level of 85 dB(A) for implementation of hearing loss prevention programs[1]. But, despite engineering and administrative controls, workers continue to exceed their recommended daily noise dose. Hearing protection devices are worn as a final defense against noise overexposure, but many workers have difficulty communicating or detecting warning signals while wearing them. New electronic technology has been integrated into conventional hearing protectors to allow for some degree of sound restoration. Research is currently being carried out within NIOSH, Pittsburgh Research Laboratory (PRL) to evaluate the performance of sound restoration hearing protectors. Due to certain features of the devices, such as their non-linear performance and possible manipulation of electronic settings, there are obstacles to testing them using the existing standard hearing protector test methodology (ANSI S12.42-1995 and ISO 4869-3:1997). These and other issues related to testing these devices are outlined within this paper, and possible solutions are discussed. Measures of attenuation properties have been done on a set of the devices and preliminary findings indicate that new test methods, or at least modifications of existing methods, must be developed to accurately determine device performance. Furthermore, it is necessary to know not only the attenuation properties of such devices, but also the degree to which speech intelligibility or recognition of warning signals is preserved, as compared with conventional hearing protectors. As additional data is collected a more accurate and reliable test methodology will be developed, and a more comprehensive picture regarding device performance will be determined and disseminated.

1. INTRODUCTION

NIOSH has identified noise-induced hearing loss as one of the most common occupational diseases. Data obtained from a large sample of employed National Health Interview Survey respondents indicate an 11.4% prevalence of hearing difficulty of which 24% can be attributed to employment[2]. Hearing difficulty attributable to employment is differentially distributed across

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various industries. A NIOSH analysis of a large sample of audiograms showed that at age 50 approximately 90% of coal miners and 49% of metal/non-metal miners had a hearing impairment[3,4]. Engineering and administrative controls are implemented at job sites to reduce the sound levels to which employees are exposed, regardless of industry. Despite these controls many workers continue to exceed the recommended daily noise dose of an 85 dB(A) average sound level for an 8-hour shift. Hearing protection devices (HPDs) serve as the final line of defense in decreasing a worker's daily noise dose; however, workers will often complain that while wearing HPDs they are unable to understand speech or detect warning signals. Consequently, speech interference has become a bothersome and potentially dangerous aspect of today's noisy work environment.

Over 50 manufacturers have developed and sell at least 240 types of hearing protectors[5]. Many HPDs are designed to achieve the highest attenuation values possible. Devices with high sound attenuation provide the user with the greatest amount of protection from noise; however they become problematic when the user's ability to understand speech is compromised. Current standards are primarily concerned with protecting workers from damaging levels of noise and, in general, disregard any negative impact on communication ability. "Overprotection" or preventing a worker from hearing speech or other warning signals can increase the possibility of accident or injury in the workplace. This effect is typically seen with workers who are suffering from impaired hearing[6]; although this can also be noticed with normal hearing individuals due to the reduction of important consonant cues[7]. Because of these problems, developers of HPDs recognize the need for improved technology, and have moved towards producing devices that have less interference on audibility.

New electronic technology has been incorporated into standard HPD design to restore some of the sound that is lost through attenuation. Such "sound restoration" technology has been developed to work with circumaural earmuffs as well as insert earplugs. To date there is no ANSI or ISO standard method for testing sound restoration HPDs, except in their passive mode. Without a standard method manufacturers and researchers can test these devices using methods based on convenience or use methods based on the existing standards for testing passive hearing protectors. Therefore, comparison of experimental results is difficult due to variations in test methodology. An overview of the obstacles and potential solutions will be presented, highlighting current work at PRL, NIOSH researching the efficacy of these devices for potential use in the mining industry as well as other occupational sectors.

2. OBSTACLES

A. Design

Some of the most fundamental obstacles to accurate and efficient testing of sound restoration HPDs lie within the physical design. There are a variety of ways in which the electronic mechanism in sound restoration HPDs can be assembled and function. This can vary by manufacturer and type of ambient noise for which the device is designed. Various controls may be on the devices to allow the user to modify the response to a desirable setting. Controls for power, volume, frequency filters, or impulse reduction may be found on sound restoration HPDs. This contrasts with standard passive hearing protectors that provide attenuation though physical characteristics or acoustic filters that do not have electronic components. Some devices may simply have a control for "on" or "off" while others have a range of settings that can be adjusted. When a range of settings is possible it is difficult to determine how many separate settings should be analyzed. It is unreasonable to assume that every possible setting should be evaluated, when discrete values do not visually exist (for example, a dial with no markings). Furthermore, if some set of intervals are indeed tested, it would be necessary to have standard intervals in order to correlate results between devices with dissimilar dials. In addition, a method must be developed to ensure that the determined intervals are analogous for sound restoring type HPDs.

Devices also differ in regard to "sidedness." This is the distinction between the presence of controls on both sides (to manipulate output to each ear independently) or one control that affects both sides of the HPD. For devices with dual controls it is necessary to assure that testing is conducted with balanced output between sides. Variations in design of sound restoration hearing protectors are beneficial to the wearer; the more flexibility a potential wearer has in adjusting the output to fit their comfort level, the more likely that the HPD will consistently be worn. However, many possible variations pose problems when attempting to research the true output of a device, and in producing reliable, replicable results that are comparable across a wide diversity of devices.

Variation in HPD placement must also be controlled. The existing standards require three repeated measures of each HPD with reposition of the device between each measure When performing multiple tests each device must be placed on the test fixture in exactly the same manner. Visually, placement may appear to be the same, but small gaps or leaks may exist. If the physical volume under the ear-cup changes due to placement, resulting attenuation data can vary. Results between tests of the same device can be skewed when a device is removed from the fixture for multiple measurements, or to test the other side as would be the case with a single sided test fixture. Placement variability is difficult to detect and is often overlooked or mistaken for electronic performance; therefore controlling it is one of the most vital aspects when evaluating the performance of sound restoration HPDs.

B. Measurements

Optimal measurements for evaluation of sound restoration hearing protector performance must also be considered. Standard hearing protector test methodology examines attenuation of HPDs as measured by human subjects[8] or on acoustic test fixtures[9,10], but these standards apply to devices in a passive condition. To evaluate the performance of sound restoration HPDs additional testing must be performed. At a minimum, it is necessary to document how changes in any device control affect the output for individual frequency bands. It also will be necessary to evaluate effects of sound restoration HPDs on speech intelligibility. Test protocols evaluating the effect of HPDs on speech intelligibility are abundant but vary based on subject hearing status, speech-to-noise ratio, background noise, the HPD being studied, and other factors. A standard method exists to calculate Speech Intelligibility Index[11] SII, which proves to be useful when determining the effects a HPD may have on speech intelligibility; but there is no standard method for implementation of the SII. Finding the proper balance of test methodology to adequately define the function and performance of sound restoration hearing protectors is necessary to provide useful guidelines for proper selection.

Determination of stimulus input intensity is yet another important aspect in regard to optimal measurement. Sound restoration hearing protectors do not perform linearly. Most devices are designed to "cut off" or no longer restore sound above 82 or 85 dB(A), depending on the device. It is of value to know how a device will perform at levels above and below this cut off level, because this is more typical of realistic occupational situations. By testing some input level above and below the device's cut off one can assess the device performance when the worker moves between various levels of noise. This information is more representative of the real world performance of the protector.

C. Other

When electronic components are involved there is always the possibility of malfunction leading to erroneous test results, or non-functional equipment. Electronic malfunction may happen in such a way that the user is unaware that the device is not functioning as intended. For example, if using a filtering mechanism, a naive listener may not detect the difference that the filter should make, and therefore a malfunction would not be noticed. This particular situation would potentially endanger the safety of the wearer if warning signals are not detected or if noise is not properly attenuated. One would assume that manufacturers of sound restoration HPDs practice quality control methods to ensure the proper functionality of their products. However, devices can become damaged due to shipping, storage, or through user handling as well as manufacturing errors. The type, quality, and assembly of components comprising the electronic circuitry also affect proper function of a device. If quality components are not used, or assembly is not done according to a proven, reliable, and skilled method, breakdown is more likely. When testing sound restoration hearing protectors it is necessary to know that a correctly functioning representative sample is being analyzed. To date, 4 devices acquired for evaluation by NIOSH, PRL were received defective or developed a fault during the course of testing.

3. POSSIBLE SOLUTIONS

Much of the research done to this point has shown that there is little or no benefit to using sound restoration HPDs in preserving speech intelligibility as compared to passive hearing protectors. Some electronic devices have achieved equal, and in some cases lower, speech intelligibility scores than comparable passive hearing protectors for hearing impaired[12] and normal hearing subjects[13,14]. It is difficult to directly compare much of the work completed to date because of differences in test methodology or design of the device. Due to discrepancies in test methodology and findings it is necessary to step back to testing the most basic elements. Testing the attenuation of the hearing protectors using one-third octave bands will provide the most basic information for evaluating performance. By evaluating the effects that manipulation of any controls has on the output of the devices one can determine, fundamentally, if they are performing as expected (for example a volume control changes intensity or a frequency adjustment changes frequency accordingly) in a consistent manner for a given broadband noise source. If attenuation test results are not consistent, then one cannot expect higher level measurements such as speech intelligibility to be meaningful.

After evaluating the performance of a group of HPDs on such basic measures, a next logical step is to test the ability of normal hearing subjects to identify warning signals and then move on to speech intelligibility measures. The overall strategy is to move from simple tasks to more complex tasks. This also applies to first testing with normal hearing subjects and then with hearing impaired subjects.

When developing the test protocol, the previously mentioned obstacles must be taken into consideration, and appropriate methods of controlling those obstacles implemented. Two issues exist when controlling for variability: 1) variability in placement of the device, and 2) variability of settings of any controls. A 2-sided test fixture (2 separate internal microphones) eliminates the need to remove the HPD to test the opposite side. Using such a device will allow the researcher to examine exactly how the device performs for both sides simultaneously thereby lessening variability due to placement. Of course, three separate measures will still be necessary to comply with existing standards, but testing both sides at one time reduces test time as well as possible placement errors.

To overcome obstacles posed when attempting to accurately retest the various settings on the device, a simple marking system can be used. Adhesive markers can be used to delineate just on, half on, fully on, etc. when visible marks are not present on the dials/controls. When visible marks are not present on the device controls, one may attempt to measure the output of the HPDs to precisely determine specific settings in relation to percent of dial turn. In theory this would assure that all measures are done with equal output, regardless of minor differences noted in dial settings. However, realistic use of the devices would not require such precision. It is more likely that a user will adjust any dials based on physical properties (tactile, visual, and/or auditory) rather than attempting to adjust the dial to some specific predefined level. This leads to two possible options for testing intermediate control/dial settings. The subject could adjust the controls to the desired settings when instructed by the experimenter; or the experimenter could visually set the dials to the desired levels and instruct the subject not to change the settings. The first method more closely matches realistic use of the devices, but allows for greater inter- and intra-subject variability. The second method reduces variability but does not replicate realistic use. The method chosen must eliminate any unnecessary complications while attempting to determine exact output levels, and lead to a time efficient test protocol.

For speech intelligibility testing, two similar options exist for determining the optimal settings of the hearing protectors. It is not reasonable to assume that all users of sound restoration HPDs would achieve the greatest benefit in speech understanding with the same control settings; therefore a consistent manner of determining optimal settings for testing must be developed. The first option is to instruct the subject to don the HPD after an explanation of the use/purpose of any controls and practice time. Then, the subject shall adjust the device to the level felt to be the most beneficial. The subject would then undergo speech intelligibility testing using these self-determined settings. This option, as mentioned previously, allows for much intra- and inter-subject variability but is consistent with realistic use. The second option requires the experimenter to set the control to some predefined setting (perhaps the level visually determined to be 50% on) for speech intelligibility testing. As previously mentioned this method reduces variability but also reduces the realistic quality of user chosen settings. It is important to note that the settings used by workers in various occupational settings will depend on their own hearing status as well as their noise exposure and audibility needs. Sound restoration hearing protection devices will not necessarily be used at some predefined setting and one setting will not be optimal for all wearers. Allowing test subjects to determine their own settings more accurately replicates realistic use of a given device.

To fully quantify the effects of sound restoration technology on incoming signals, it will be necessary to evaluate the device using a variety of background noises. It is necessary for the background noise to vary in both frequency and intensity characteristics. The frequency spectra for tests should be representative of various noises found in occupational settings. Muliple spectra are necessary as there is not a single specific frequency spectrum that best exemplifies all occupational settings. Furthermore, at least three intensities should be evaluated to express the intensity range in which the sound restoration devices might be used. These stimulus levels should consist of an intensity well below the Mine Safety and Health Administration (MSHA) action level of 85 dB(A), an intensity between the MSHA action level and Permissible Exposure Level (PEL) of 90 dB(A), and an intensity well above the PEL. Suggested levels are 78, 88, and 98 dB(A), respectively. This would cover a range of intensities near and above sound levels considered to be hazardous.

The last major concern is that of electronic malfunction. The reliability of the electronic components is an important factor that cannot be controlled by the researcher. Many of these devices are rechargeable or require a battery to provide power. Thus, it is important that the user have some knowledge of the sound they should receive from a device. It is also necessary for wearers to recognize when a device is not adequately powered and how to remedy the problem. If a device is not functioning correctly the worker will not receive the full benefit of the sound restoration device.

4. CURRENT RESEARCH

Work at NIOSH, PRL is currently focused on evaluating the most basic level of function for sound restoration hearing protectors. The purpose of this research is to determine the usefulness of such devices in improving audibility of speech and auditory safety signals in the mining industry. Several stages of testing have been carried out on a selection of sound restoration hearing protectors. Attenuation testing was done using a single-sided acoustic test fixture, specifically, a trapezoidal anodized aluminum device the size of an adult human head with a soft, flesh-like, imitation pinna. Inside the fixture is one Etymotic Research ER-11 ½ inch microphone #2051.

The entire device was mounted on a tripod and set in the center of a reverberant chamber. Hearing protectors were tested both in the passive mode (electronics *not* activated) and with the electronics activated using maximum settings of all available control manipulations. One-third octave attenuation properties were calculated for 3 broadband noise sources with varying octave band spectra[15] (NIOSH noises 2, 4 and 6).

Attenuation results were not predictable. A large amount of variability was detected between the devices, within repeated tests of the same device, and between sides of a single device. When analyzing attenuation by third- octave bandwidths, differences greater than 3 dB were found for 49% of the comparisons of attenuation values between the right and left sides of the same device. Excessive differences of greater than or equal to 10 dB were found for 1.5% of the measures taken between sides of the same device. While some small differences in attenuation values between sides are to be expected due to design factors of the hearing protectors, a difference of 10 dB is excessive, especially considering that during realistic use, such difference could cause one ear of a wearer to be adequately protected and the other ear to be overexposed. Furthermore, although control manipulation generally resulted in the correct corresponding change in attenuation, these frequency and intensity adjustments did not have a linear effect that was predictable across devices.

Many instances were found where the same side and same setting of the same muff yielded different results. At times, visual inspection revealed no detectable differences, but the results varied, note Figures 1 and 2 below. Devices were repositioned between measures (per ANSI S-12.42-1995 and ISO 4869-3:1997), but settings and background noise remained constant. Figures 1 and 2 indicate variability regardless of settings (passive mode or electronics activated). Note the variability in low frequency attenuation data between measures. Differences of 7-20 dB(A) for the 50-315 Hz one-third octave bands were observed. Since large variability exists in the passive mode, Figure 2, it can be deduced that placement, and not necessarily electronics, is the underlying cause of poor inter-measure repeatability.

As the devices were manipulated by the researcher, the results changed, further supporting placement as a source of error. Difficulty in achieving a proper and consistent acoustic seal further complicates the ability to analyze the performance of circumaural type hearing protectors (sound restoration or passive). Seams between physical components of test fixtures[16] and the presence or absence of a false plastic, skin[17] may lead to discrepancies in results across earmuffs and within repeated testing. Any or all of these factors may have contributed to the variability in attenuation data. Inconsistent electronic performance from the HPD is another potential source of error.

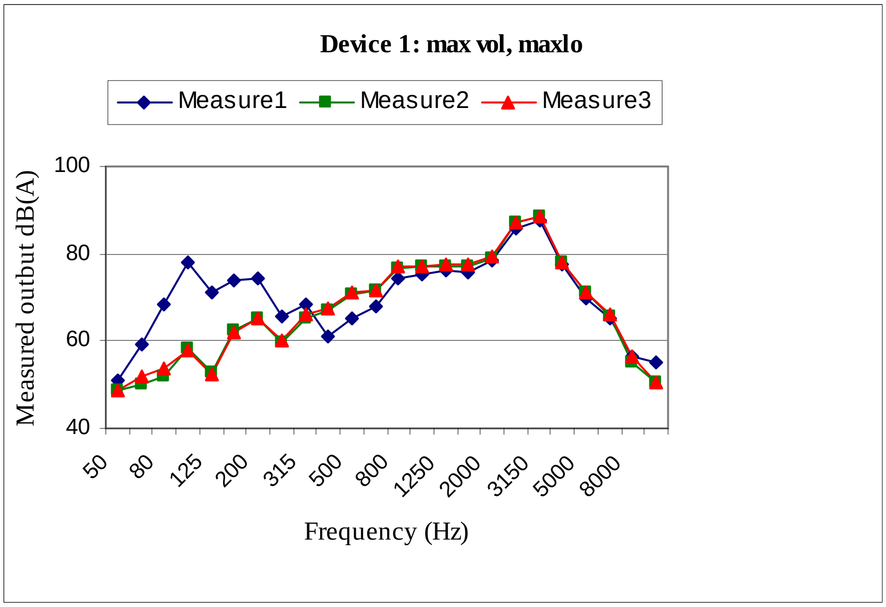

Figure 1: Right side output plots for 3 measures of 1 hearing protector with volume and both frequency filters set to maximum. The HPD was repositioned between measures.

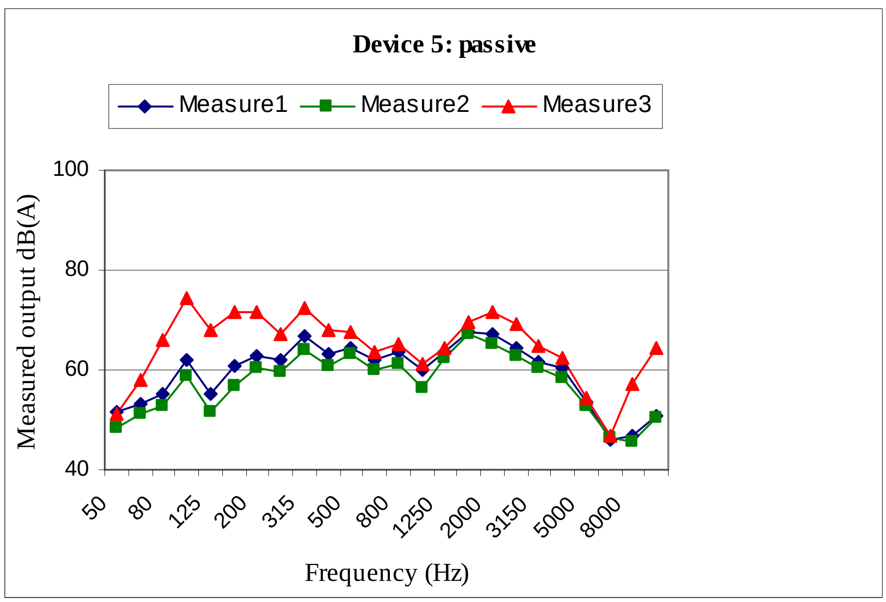

Figure 2: Left side output plots for 3 measures of 1 hearing protector with all electronics off (passive mode). The HPD was repositioned between measures.

Because the reliability of the previously collected data is questionable, the same set of HPDs along with others is being re-evaluated using a different test apparatus. A 2-sided hearing protector test fixture with two internal ½-inch condenser microphones is now being used. The fixture does not have imitation pinnas and is designed specifically for evaluating the performance of circumaural hearing protectors per ISO 4869-3:2007. This setup eliminates the need to move the HPD to test both sides as it can acquire data binaurally thus reducing the possibility of errors due to placement. The current standard test method for passive hearing protectors (ANSI 12.42-1995) requires repositioning of the hearing protectors for three measurements of the device. Therefore, the possibility remains for placement differences between measures of a device, but the possible errors are reduced from 6 (3 repeated measures x 2 sides) to 3 (3 repeated measures total for both sides). Repositioning errors are representative of realistic use of hearing protectors. Table 1 shows a representative example of the improved test-retest reliability of the 2-sided test fixture. Although statistical analysis is incomplete at present, the preliminary trend indicates an increase in test/retest reliability. The A-weighted attenuation values for three repeated measures of two separate devices are shown for the right and left sides of the hearing protectors. Device 7 had the volume and low frequency filter set to maximum, while device 4 had the volume, low frequency and high frequency filters set to maximum. Different settings contributed to the overall differences in attenuation values *between* the devices. The devices were repositioned on the test fixture between measures. Note shaded areas A and B. A represents the difference in attenuation values between sides of the same HPD for a given measure as read across the table. B represents the averaged attenuation values for the repeated measures of the same side of a single HPD as read down the table. Notice that A-weighted attenuation values do not differ by more than 0.5 dB(A) between measures of the same side of a device indicating improved test retest reliability. The right/left comparisons show a greater difference between sides of a single device. Differing attenuation values between the right and left sides suggest that although placement issues may have been controlled for, design features may cause variable attenuation between the sides of a single device. Figure 3 displays the one-third octave attenuation measures for the left ear-cup of those same devices. Notice consistent results for multiple retests of a device- it is difficult to discern 3 separate measures on the graph because the results for the repeated measures were nearly identical.

Table 1: A-weighted attenuation values showing test/retest of 2 types of sound restoration hearing protectors.

Device #	Test	Right attenuation	Left attenuation	**A**
7	1	11.6	8.3	**3.3**
7	2	11.8	8.4	**3.4**
7	3	11.7	8.3	**3.4**
Device 7 **B**		**11.7**	**8.3**	
4	1	3.9	5.8	**1.9**
4	2	4.5	5.5	**1**
4	3	4.4	5.2	**0.8**
Device 4 **B**		**4.3**	**5.5**	

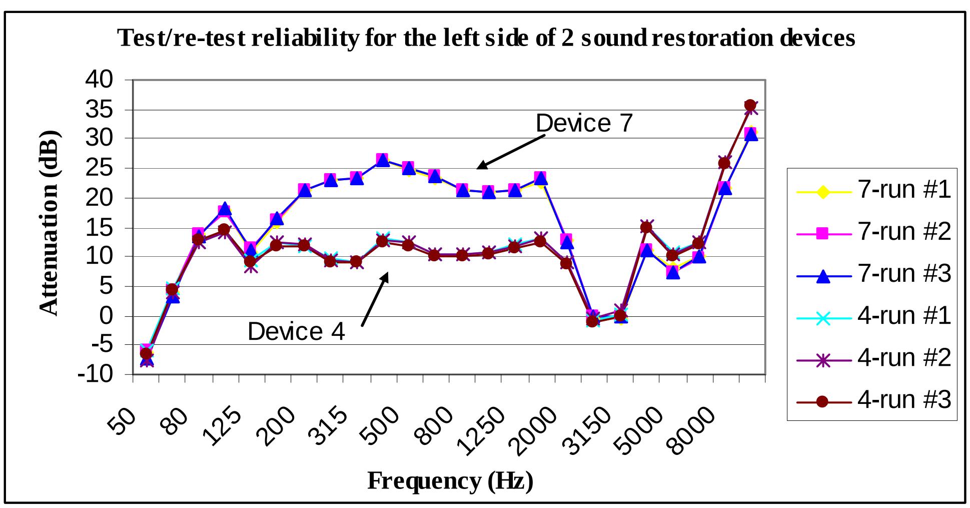

Figure 3: Test/re-test reliability of the attenuation of 2 sound restoration hearing protectors.

5. Conclusion

Use of the 2-sided acoustic test fixture has led to greater reliability when testing sound restoration hearing protectors. The primary concern with using the previous, single-sided fixture was the lack of reliability of attenuation results obtained between identical measures of a device. With such differences between measures, it was difficult to state anything conclusively about the performance of the HPDs because it was unclear if the testing results were truly reflective of device performance. Because the 2-sided acoustic test fixture has greatly improved the test/re-test reliability, as evident through consistent attenuation results, the performance of the devices can now be confidently be measured and quantified. Since the remaining variability between *sides* of a single device occurred with both test fixtures, it is likely due to manufacturing or functional factors rather than test methods or testing apparatus. For example, a device with all of the electronic controls housed in one earcup may have a greater difference in attenuation measures between sides than a device with electronic controls in each earcup. Such differences could be due to mass differences of that earcup or due to differences in electronics as the signal is routed from the microphone to the receiver. As more devices with various designs (single versus dual earcup controls) are tested the effects of such physical components on acoustic performance will become better understood. However, the primary concern, lack of reliability for identical measures of a single device, has been sufficiently overcome.

While the overall goal for this particular research endeavor is to determine the efficacy of sound restoration HPDs in order to provide recommendations on their use in mining, as well as other occupational settings, other objectives will also be met. One such objective is the development of a standard method for testing the performance of these devices. The development of a standard methodology will allow the performance of such devices to be easily compared. Manufacturers, researchers, occupational medicine professionals, and hearing protection users will benefit from a standardized test protocol. This will assure that all devices are measured equally according to a repeatable procedure yielding consistent and meaningful performance results.

Many steps must be taken in moving towards the final goal of providing consistent and meaningful recommendations on the use of sound restoration HPDs. Workers struggle daily with protecting their hearing while maintaining sufficient audibility. They must be provided with guidance in choosing the most suitable device for them and their work environment. The ideal device will provide adequate protection from noise overexposure, while allowing for communication and identification of warning signals. Recommendations for use of these devices must be developed for a variety of occupational settings and for normal hearing as well as hearing impaired workers. Occupational safety and health officials must be provided with accurate information so that an effective policy regarding use of these devices can be established. Recommendations for selection of sound restoration hearing protectors based on maximum recognition of critical sounds will further advance occupational safety and health standards.

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