A LABORATORY SIMULATION OF SELECTED IN-FIELD INFLUENCES ON HEARING PROTECTOR PERFORMANCE

M. Y. Park and J. G. Casali
Auditory Systems Laboratory
Human Factors Engineering Center
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061

ABSTRACT

Overestimation of hearing protector noise attenuation, as based on laboratory-obtained data, combined with several in-field factors which often degrade protector performance, poses the threat of underprotection for the user. This research investigated the effects of several work-related factors, including wearing time, movement activity, and fitting procedure, on the frequency-specific attenuation achieved with a foam cushion earmuff, two types of earplugs, (slow-recovery foam and flanged polymer), and an earmuff over foam earplug combination. Using a real-ear-attenuation-at-threshold testing procedure, attenuation data were collected from 40 subjects at nine test frequencies. Occluded thresholds were obtained before, during, and after the movement activity task, so that the effects of wearing time and task activity could be determined. The tasks were designed to elicit movements akin to those performed in the typical industrial workplace. The results indicated that achieved attenuation was significantly decreased as a function of time, and that trained-fit provided noticeably greater attenuation than subject-fit without training, though these changes were device-specific. Overall, the study illuminated the strong influence of in-field factors on hearing protector effectiveness, and demonstrated the need for laboratory attenuation tests which yield more realistic results.

BACKGROUND

Personal hearing protection devices, (hereafter HPDs) have emerged as a popular defense against noise-induced hearing loss. Occupational Safety and Health Act Regulation 1910.95 has solidified the need for effective HPDs in general industry with the requirement that all employees exposed to 8-hour time-weighted average exposures of 85 dBA or more be supplied with HPDs (OSHA, 1988). Though engineering noise abatement is emphasized as a first line of attack, it is often infeasible, too expensive, or ineffective. As such, for many workplace environments, current OSHA industrial enforcement practice allows HPDs to augment, or in some cases supplant, engineering and/or administrative countermeasures. Their use is also becoming more popular for the general consumer using power tools or firearms, for spectators at loud events such as automobile races, and for musicians (Toufexis, 1988).

HPD Testing and Rating

In selecting an HPD which is adequate for a particular exposure problem, the industrial safety officer or end-user must rely on the Noise Reduction Rating (NRR), required by the EPA on HPD packaging, as a performance criterion (EPA, 1984). Unfortunately, the rating is known to indicate substantially higher protection than is actually provided under field conditions, and therefore attempts have been made at de-rating the NRR (on a post-hoc basis) to obtain a more realistic estimate (Berger, 1983a). To obtain the spectral attenuation data used in computation of the NRR, a standard testing protocol is applied using psychophysical threshold determination tests in highly controlled laboratory conditions (ANSI, 1984). In such tests, well-trained subjects are tested with new, properly-fit HPDs while they are seated quietly, with near-fixed head position, for a very short wearing period. By contrast in the field, individuals often wear poorly-fit HPDs for long periods while undergoing physical movement and exertion associated with tasks at hand. Obviously, the standard laboratory test procedure is not intended to account for the typical in-workplace influences on HPD protection performance. New test standards designed to yield more realistic estimates of HPD performance are needed. To afford the control necessary to provide intra- and inter-laboratory test replicability, such standards must be implemented under laboratory conditions using well-specified procedures.

Present Study Objectives

With the above need in mind, a laboratory-based procedure was devised to determine the influence of the in-field variables of movement activity during a prolonged wearing period and HPD fitting procedure on achieved HPD attenuation. These potential influences were of initial comparison interest because the current testing standard (ANSI S12.6-1984) yields protection values for a well-supervised fit of the device immediately after it is donned on a near-motionless subject. For comparison purposes, one attenuation measurement was obtained under conditions similar to those of the standard, i.e., with a trained fitting of the HPD before the subject underwent any movement.

On the basis of data on a broad range of fitting strategies, it is apparent that performance of certain HPDs may be susceptible to the level and type of training given the user (e.g., Abel, Alberti, and Riko, 1981; Casali and Epps, 1986; Casali and Lam, 1986). For this study, the two fitting conditions were intended to represent the extremes of those which might be given an industrial worker.

To investigate movement activity and wearing time effects, two paced movement tasks were devised. Since previous research (e.g., Abel and Rokas, 1986; Berger, 1981; Cluff, 1989) has suggested that temporomandibular movement may reduce attenuation for certain, but not all, insert HPDs, a controlled task representative of chewing gum or tobacco, eating, and talking while occluded was used as one activity condition. In the other activity condition, a highly kinematic physical work task was performed by the occluded subject. Each activity task was performed for two 30-minute periods within a single two-hour HPD wearing period. Previous studies (e.g., Berger, 1981; Casali and Grenell, 1989; Krutt and Mazor, 1980) have shown small attenuation reductions with various HPDs over similar wearing periods, but these experiments were not designed to simulate vigorous, high-activity industrial production work, along with which protection losses may be most critical.

METHOD

Subjects

Participants included 40 paid volunteers, consisting of 5 males and 5 females for each HPD condition, who were inexperienced with HPDs. Subjects were screened for normal hearing, defined as -10 to 20 dB from 125 to 8000 Hz in octave steps, using a Beltone 114 pure-tone audiometer, and had no evidence of otopathic disorders. Ages ranged from 19 to 35 years, with a mean of 23.9. Eyeglasses, ear jewelry, and headgear were removed prior to fitting the HPD.

Apparatus and Experimental Variables Implementation

HPD attenuation instrumentation. At each measurement juncture, auditory threshold data were collected using Békésy tracking procedures. Test signals for the audiograms were generated by a Norwegian-Electronics 828 system and consisted of nine 1/3 octave bands of center frequencies 125, 250, 500, 1000, 2000, 3150, 4000, 6300, and 8000 Hz, pulsed on-off at 2 Hz. Signal presentation occurred in a uniform sound-field about the subject's head via four frequency response-matched loud-speakers mounted in a sound-attenuating chamber. The audiograms were scored on-line using an algorithm on the host IBM PC/AT computer. Level calibration of the test signals was performed daily using a Larson-Davis 800-B 1/3 octave analyzer. Details of this HPD test facility and verification data for its electro-acoustic performance in accordance with ANSI S12.6-1984 appear in Casali (1988).

Activity task equipment. The within-subjects work activity task variable was implemented using a Baltimore Therapeutic Equipment Work Task Simulator, which provided controlled resistance against which the subject had to exert force at a specified pace. Using interchangeable tooling heads on this simulator, six highly kinematic standing work tasks, representative of heavy manual industrial jobs, were presented over each 30-minute activity period. Two video displays located slightly behind the subject, one to the left and one to the right, presented random digits which the subject had to monitor every 5 seconds. This forced rapid acceleration/deceleration of the head which could induce HPD slippage.

In the jaw movement condition, subjects alternated 5-minute intervals of reading aloud with a forced vocal effort, trying to maintain a 70 dBA level on an analog sound level meter display, with 5-minute intervals of chewing gum or eating a snack, to constitute each 30-minute period. This task elicited almost continuous temporomandibular movement (but no other physical activity), and afforded a controlled means of allowing jaw motion to impact achieved attenuation, much as it would for a gum-chewing or conversational worker in noise.

HPDs. Four diverse protectors were investigated in between-subjects format. These included the following, with manufacturer's most recent NRR in parentheses: Bilsom UF-1 earmuff (25 in overhead position) - a basic foam cushion earmuff; E-A-R foam plug (35) - a cylindrical, user-molded, slow-recovery foam device that must be compressed into a small diameter cylinder prior to insertion; E-A-R UltraFit plug (27) - a premolded polymer plug with three hemispherical flanges and a stem for fingertip grasp during insertion; and "double" protector (no NRR) - the Bilsom muff worn over the foam plug. This latter combination is exemplary of double protection sometimes used in very high ambient noise levels where a single HPD is inadequate.

Fitting conditions. For each subject, fitting of the HPD was accomplished under two conditions, with the trained-fit condition always preceded by the subject-fit condition (so that the subject-fit would not be influenced by the experimenter training). In *subject-fit*, the subject received the HPD in its standard industrial packaging and was asked to don it, without any assistance, according to the manufacturer's printed instructions. This mimicked some industrial employee and most consumer practices of fitting protectors without help. In *trained-fit*, the subject practiced donning the HPD after reading the manufacturer's instructions and while receiving verbal guidance and supervision from the experimenter. Then the subject proceeded into the chamber and donned the HPD on his/her own. A 70 dBA pink noise was then presented for feedback while the subject adjusted or re-fit the HPD to subjectively block the maximum sound.

Protocol. Each subject attended four sessions, each comprised of one fitting procedure and one activity task. After familiarization with the assigned activity task (jaw or work movement) procedures and practice in threshold tracking, the subject underwent a pre-task unoccluded threshold test for each 1/3 octave band. Then the HPD was donned according to the assigned fitting condition and a 5-minute stabilization period passed. *(Once the HPD was fit, the subject did not touch or readjust it for the remainder of the two-hour wearing period.)* Next, the first (pre-task) occluded thresholds were obtained, followed by the first 30-minute activity period, and then a determination of the second (during-task) occluded thresholds. Then the second 30-minute activity period passed, followed by the third and final (post-task) occluded threshold tests. At this point, the HPD had been worn continuously for two hours without adjustment, and occluded thresholds had been determined pre-task, after one hour, and again after two hours. Finally, post-task unoccluded thresholds were obtained and the subject was dismissed.

RESULTS

Pre-task attenuation was computed as the difference between pre-task occluded and pre-task unoccluded thresholds at each frequency. Post-task (two hour) attenuation was determined in the same manner. Attenuation after one hour (during the task) was computed as the difference between the second occluded threshold and the mean of the pre-task and post-task unoccluded thresholds. The dependent measure in each case was HPD attenuation in dB (linear) at each test band frequency.

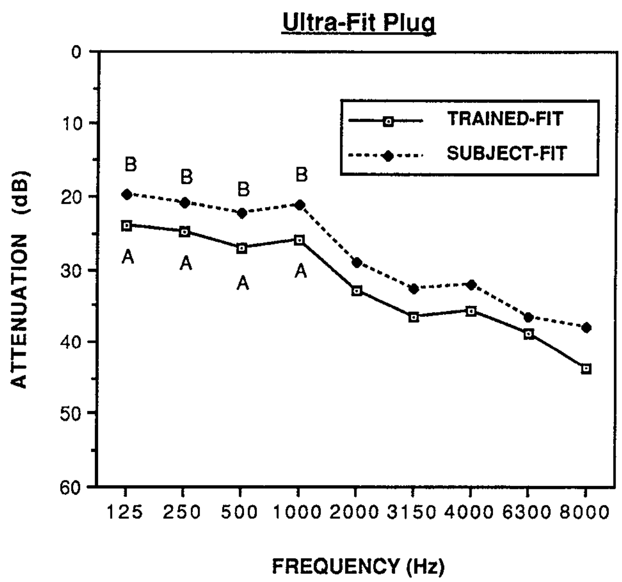
Statistical Analyses

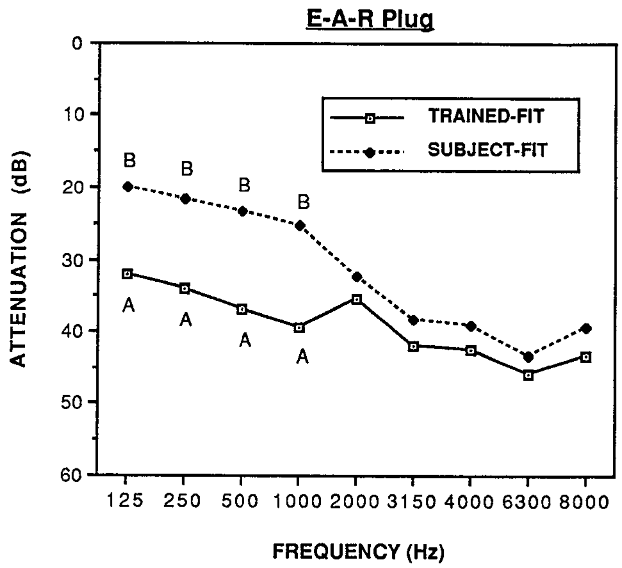
Overall ANOVA. First, the frequency-specific attenuation data were subjected to four-way analysis of variance procedures. Statistically-significant ($p < 0.05$) main effects were found for HPD and wearing time at all frequencies, for fitting procedure at all frequencies except 6300 Hz, and for movement activity at 3150 Hz. Significant ($p < 0.05$) two-way interaction effects included fitting procedure-by-wearing time at 500 and 6300 Hz, fitting procedure-by-HPD at all lower frequencies (125 to 1000 Hz), wearing time-by-HPD at all frequencies except 8000 Hz, and movement activity-by-HPD at 6300 Hz. In addition, one three-way interaction effect (fitting procedure-by-wearing time-by-HPD) was also revealed to be significant but was analyzed further only in the context of its significant embedded two-way effects.

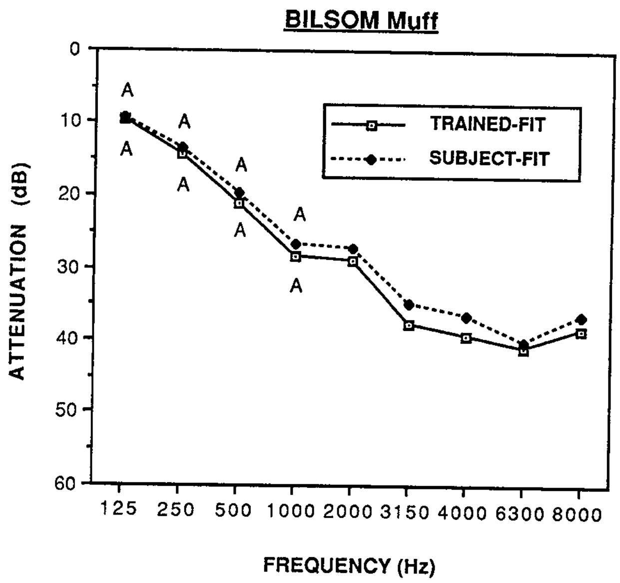
For the significant interactions, simple-effects *F*-tests were applied to the dimensions of interest, followed by Bonferroni-*t* tests for post-hoc means comparisons. Bonferroni-*t* (for wearing time) and Newman-Keuls multiple range (for HPD) tests were employed for main effect post-hoc analyses. All post-hoc tests were performed at $p < 0.05$ unless otherwise noted, and the *F*-test and *t*-test tables are not presented here due to their length. In the figures which follow, means with different letters are significantly different at $p < 0.05$.

Fitting procedure-by-wearing time interaction. The influence of the fitting procedure used in initial donning of the HPD on the stability of the device over the wearing period was evidenced by attenuation reductions at only 500 and 6300 Hz. *F*-tests on each fitting procedure indicated that attenuation reduced significantly ($p < 0.01$) over the wearing period for both fitting procedures at both frequencies. The subsequent Bonferroni-*t* test results revealed that the wearing time effect was slightly more pronounced for the subject-fit condition (an average reduction of 3.2 dB from pre- to post-task measurement) than for the trained-fit condition (an average reduction of 1.5 dB from pre- to post-task).

Fitting procedure-by-HPD interaction. The consistent influence of fitting procedure on achieved attenuation was found to be device-specific at 1000 Hz and below. All of the earplug conditions, including the muff/plug condition, were highly susceptible to fitting procedure differences, but the earmuff was not. Bonferroni-*t* tests on each HPD condition (except the muff) revealed that substantially lower attenuation was evidenced in the subject-fit condition than in the trained-fit condition. As shown in Figure 1, the attenuation difference between fitting procedures ranged from a low of 4.0 dB at 250 Hz for the UltraFit to a high of 14.1 dB at 1000 Hz for the E-A-R foam plug. For the combination, foam plug, and UltraFit plug, the fitting procedure effect was very pronounced at 1000 Hz and below. (The apparent differences above 1000 Hz for the UltraFit plug were not analyzed post-hoc since they were not significant in the overall ANOVA.)







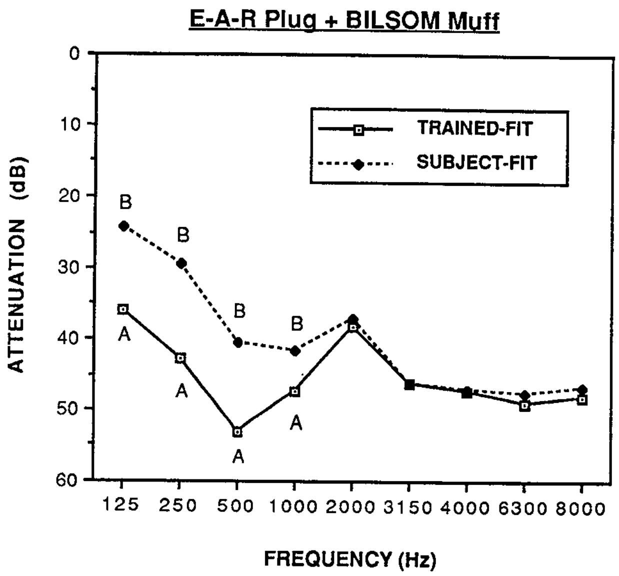
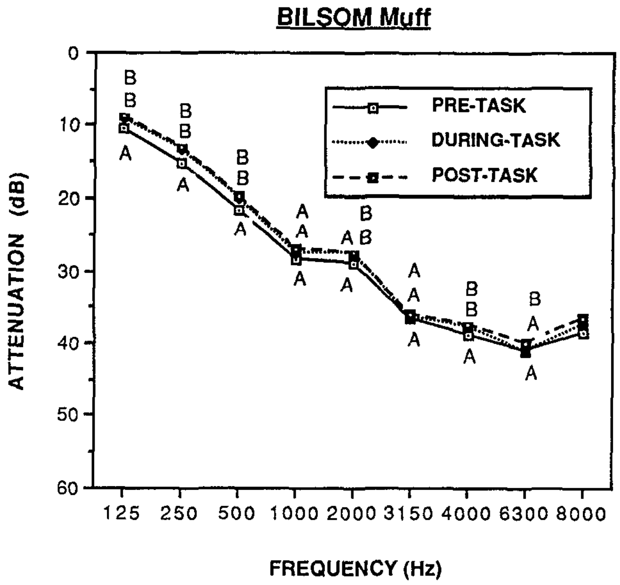
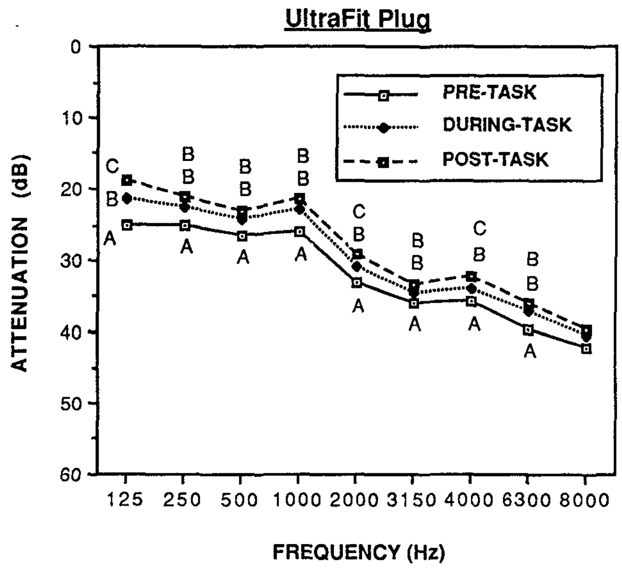


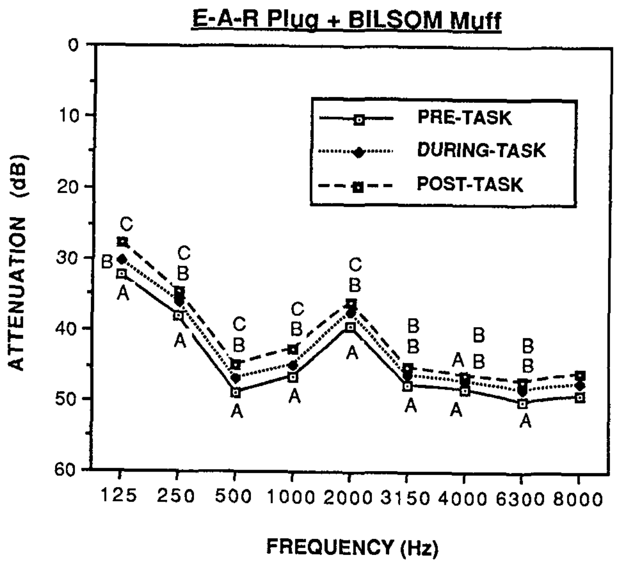
Figure 1. Attenuation with each fitting procedure for each HPD.

Fitting procedure main effect. This main effect demonstrated that trained fitting afforded significantly ($p < 0.01$) higher protection at all frequencies (except 6300 Hz) than subject fitting. The attenuation difference between fitting procedures was 2 to 8 dB depending on frequency, but was generally largest at 1000 Hz and below, as borne out in the interaction of fitting procedure with HPD.

Wearing time-by-HPD interaction. Time-dependent changes in achieved attenuation were device-specific, thus having particular bearing on HPD selection. The attenuation provided by all HPDs except the foam plug decreased significantly over the wearing period at all frequencies excluding 8000 Hz. According to the Bonferroni results on each HPD (Figure 2), these dB attenuation reductions were quite consistent across frequency for the UltraFit and combination protectors, but less so for the muff for which attenuation changes were not significant at 1000 and 3150 Hz. In the case of the muff/foam plug combination, a frequency-specific attenuation decrease occurred over the wearing period. However, this reduction did not occur for the foam plug alone and was less pronounced for the muff alone.







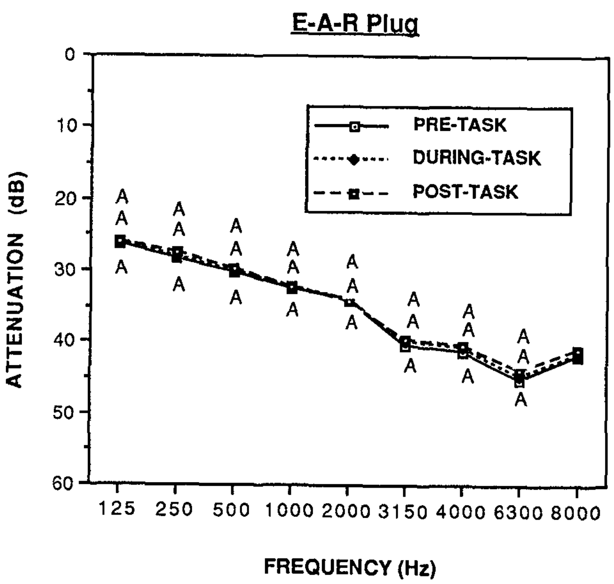


Figure 2. Attenuation over the wearing period for each HPD.

Movement activity-by-HPD interaction. Significantly ($p < 0.01$) more attenuation (by 3.4 dB at 6300 Hz only) resulted in the jaw movement condition than in the work activity condition, but only for the muff protector which tended to slip during work.

Activity movement and wearing time main effects. The activity effect at a single frequency, 3150 Hz, was negligible in a practical sense due to its small dB difference (0.8 dB less attenuation under work activity than jaw movement). However, activity did result in significant ($p < 0.01$) attenuation changes over the wearing period, as evidenced by the wearing time main effect at all test frequencies. Attenuation significantly decreased at each time juncture (from pre- to during- to post-task).

HPD main effect. This significant ($p < 0.01$) main effect (at all frequencies) was expected since it is well-known that different HPDs broadly differ in their spectral noise reduction capabilities. The Newman-Keuls test indicated that of the three individual HPDs used, the E-A-R foam plug provided the highest attenuation across all frequencies. As expected, the combination protectors offered the highest noise reduction of all HPDs tested, approaching the bone conduction limits estimated by Berger (1983b) at 2000 Hz and above.

DISCUSSION AND CONCLUSIONS

This study demonstrated that achieved spectral noise protection significantly decreased over the activity period, indicating that certain protectors have a tendency to loosen under bodily movement. According to the mean attenuation change (across the nine test frequencies) from pre-task to post-task periods, the UltraFit plug showed the largest reduction in attenuation (-3.8 dB), corroborating the result (a 4 dB drop) of another triple-flanged plug (the North Com-fit) evaluated by Cluff (1989). The foam plug was the most stable HPD over the activity period. The mean attenuation of the combination protectors deteriorated by 3.3 dB, which was about 1 dB more than the combined noise reduction of the foam plug (by -0.6 dB) and the muff alone (by -1.5 dB).

Achieved attenuation was generally poorer for the subject-fit than the trained-fit condition. This clearly indicates that with only brief (i.e., five minutes) interactive training on HPD fitting, subjects can markedly improve their noise protection levels as compared to those obtained with the use of only manufacturer's package instructions. However, this improvement was highly device-specific, and especially pronounced for insert protectors, but did not occur for the muff. This is perhaps because the muff is straightforward to don, especially when compared to user-molded earplugs (Casali and Lam, 1986).

The following general conclusions can be drawn:

1) Compromised hearing protection and OSHA regulation noncompliance may potentially result if workers initially fit HPDs poorly and/or undergo vigorous movement activity. Thus, proper user training and protector selection may enhance protection.

2) The slow-recovery foam plug appears to be resilient to attenuation loss due to either head/torso or temporomandibular movement.

3) Double protectors (muff over plug) provide additional protection for extreme noise environments, while having some disadvantages, such as interference with speech communications due to high attenuation.

4) For accurate estimation of in-field influences, the current testing standard (ANSI S 12.6-1984) requires revision. Because experimenter-supervised fit of the HPD (as per ANSI 12.6-1984) is not realistic, actual HPD performance may be overestimated. Rather, the subject-fit investigated in this study is probably more representative of workplace practices, because in many cases the package instructions are the sole information provided to workers.

ACKNOWLEDGEMENTS

This research was supported in part by the National Institute for Occupational Safety and Health, Centers for Disease Control, project number 1 R01OH02540-01. Thanks are due Roy Fleming and Barry Lempert of NIOSH for helpful suggestions.

REFERENCES

Abel, S. M., Alberti, P. W., and Riko, K. (1981). User fitting of hearing protectors: Attenuation results. In P. W. Alberti (Ed.), *Personal hearing protection in industry* (pp. 315-322). New York: Raven Press.

Abel, S. M. and Rokas, D. (1986). The effect of wearing time on hearing protector attenuation. *Journal of Otolaryngology 15*(5), 293-297.

ANSI S12.6 (1984). *Method for the measurement of the real-ear attenuation of hearing protectors.* New York: American National Standards Institute, Inc.

Berger. E. H. (1981, June). *Details of real world hearing protector performance as measured in the laboratory.* Noise-Con 81, North Carolina State University, Raleigh, N.C.

Berger, E. H. (1983a). Using the NRR to estimate the real world performance of hearing protectors. *Sound and Vibration*, 17, 12-18.

Berger, E. H. (1983b). Laboratory attenuation of earmuffs and earplugs both singly and in combination. *American Industrial Hygiene Association Journal, 44*(5), 321-329.

Casali, J. G. (1988). A computer-controlled facility for hearing protection research and testing, Verification re ANSI S12.6-1984. Blacksburg, Va: VPI&SU, IEOR No. 8801.

Casali, J. G. and Epps, B. W. (1986). Effects of user insertion/donning instructions on noise attenuation of aural insert hearing protectors. *Human Factors*, *28*(2), 195-210.

Casali, J. G. and Lam, S. T. (1986). Effects of user instructions on earmuff/earcap sound attenuation. *Sound and Vibration, 20*(5), 22-28.

Casali, J. G. and Grenell, J. F. (in press). An exploratory study of moderate physical activity and selected design attribute effects on earmuff attenuation. *American Industrial Hygiene Association Journal.*

Cluff, G. L. (1989). Insert-type hearing protector stability as a function of controlled jaw movement. *American Industrial Hygiene Association Journal, 50*(3), 147-151.

Environmental Protection Agency (1984). Product noise labeling. *40 Code of Federal Regulations*, 211, 120-137. Washington, D.C.: U.S. Government Printing Office.

Krutt, J. and Mazor, M. (1980). Attenuation changes during the use of mineral down and polymer foam insert-type hearing protectors. *Audiology and Hearing Education*, Winter, 13-14.

Occupational Safety and Health Administration (1988). Occupational noise exposure. *29 Code of Federal Regulations.* 1910.95, 176-191. Washington, D.C.: U.S. Government Printing Office.

Toufexis, A. (1988). A fire hose down the ear canal. *Time*, Sept. 26.