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Attenuation Performance of Four Hearing Protectors under Dynamic Movement and Different User Fitting Conditions

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An experiment was conducted to determine the effects of movement activities and alternative fitting procedures on protection levels afforded by four hearing protection devices (HPDs). Psychophysical attenuation measurements at nine one-third-octave bands from 125 to 8000 Hz were obtained prior to, during, and following a 2-hr wearing stint that included periods of either highly kinematic but controlled work activity or vigorous temporomandibular movement. The 40 subjects, who were nonusers of HPDs, initially fit the protectors according to either the instructions on the package (i.e., subject fit) or after receiving interactive training on proper fit (i.e., trained fit). Thereafter no further protector adjustments were allowed during the wearing period. The subject-fit condition resulted in significantly lower protection levels, from 4 to 14 dB, at 1000 Hz and below for a premolded polymer earplug, a user-molded foam earplug, and a double protector consisting of a muff over the foam plug. The muff alone was significantly more resilient to fitting effects on attenuation than were the plugs. Movement activity caused up to a 6-dB significant reduction in frequency-specific attenuation over time for the premolded plug, muff, and muff-plug combination. The compliant foam earplug was largely resistant to either type of movement effect but did benefit more than the other devices from use of the trained-fit procedure. Implications of the results for hearing protector testing protocol, device selection, and user training are discussed.

INTRODUCTION

Hearing Loss Countermeasures

Permanent hearing loss is a frequent and tragic consequence of exposure to high-intensity sounds of industrial, military, or even recreational origin. It has long been recognized that high-level industrial machinery noise poses a major threat to workers' hearing. More recently concern has increased for the hearing of those exposed to nonindustrial noise sources, such as symphony orchestra performers (Royster, Royster, and Killion, 1989), rock musicians and listeners (Johnson,

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1987), spectators of noisy activities such as automobile racing, and consumers who use power tools.

To combat the insidious progression of noise-induced hearing impairment, effective countermeasures must be employed, one of which is personal hearing protection. Because of the expense, ineffectiveness, and/or feasibility of some administrative and engineering noise control strategies, hearing protection devices (HPDs) have emerged as a popular defense. Furthermore, the U.S. Occupational Safety and Health Act has solidified the need for effective HPDs in general industry with the requirement that all employees exposed to an 8-hr time-weighted mean of 85 dB(A) or greater be supplied with HPDs (OSHA, 1988). Based on Environmental Protection Agency estimates (EPA, 1981), this requirement affects more than 9.2 million American workers, including military personnel.

The Problem of Rating Hearing Protector Effectiveness

Spectral attenuation data and the noise reduction rating (NRR), which is computed thereof, are the primary metrics by which one can predict whether or not HPDs will provide adequate protection and OSHA compliance in a given high-noise environment. However, these attenuation data, which are required by the EPA for all HPDs sold in the United States (EPA, 1984), often overestimate actual protection values because, according to the standard protocol under which they are obtained, "the methodology is intended to yield optimum performance values which may not usually be obtained under field conditions" (ANSI, 1984, p. 1).

The standard attenuation tests are performed under highly controlled laboratory conditions using specific procedures that in no way account for the workplace influences on HPD performance. In such tests trained and motivated subjects are seated quietly for a very short wearing period and tested with new, properly fit HPDs under optimal conditions. In contrast, in the field workers may wear ill-fitted and/or damaged HPDs for prolonged periods while performing physical movements and exertions associated with the work, factors that can contribute to a poor protector seal. In other words, the standard procedures and conditions under which HPDs are tested and rated for attenuation are quite different from those in the environments where HPDs are actually used. As such, the laboratory-obtained attenuation values indicate significantly higher protection than is typically attained in the field, as verified by the surveys of Lempert and Edwards (1983) and Padilla (1976). Berger (1983a) concluded on the basis of a review of studies that the NRR overestimated protection in the field by an average of 13 dB or greater, depending on the standard deviation adjustment applied to the calculation. When one considers that the range of NRRs for currently available, standard (i.e., non-level-dependent) HPDs is about 10–35 dB, 13 dB of protection overestimation is quite significant, especially if the ambient noise is above 100 dB(A) and a marginal protector is used.

Research Objective

The intent of this study was to develop and utilize a laboratory-based protocol to estimate the influence of two important variables (HPD fitting procedure and movement activity during wearing period) on the achieved attenuation of four different HPDs. The effects of these two real-world influences were of particular interest because current HPD testing standards (e.g., ANSI S12.6-1984) provide protection ratings only for a well-supervised fit of the HPD immediately after the device is donned, which is unrealistic in the application setting.

Previous studies (e.g., Abel, Alberti, and

Riko, 1982; Casali and Epps, 1986; Casali and Lam, 1986) have indicated that the attenuation achieved may be dependent on how the subject was trained to fit the protector. On the basis of that prior work, proper fit of insert HPDs (earplugs) is generally thought to be more strongly influenced by user instruction than is that of circumaural HPDs (earmuffs). For this study two fitting conditions that were intended to represent the extremes of fitting instruction typically encountered by the industrial workers were compared. These included naive-subject fit (*subject fit*) using only HPD package instructions and trained-subject fit (*trained fit*) using HPD package instructions as well as close supervision by a trained experimenter.

Another important field influence is worker movement activity. Of particular relevance to the performance of earplugs are temporomandibular (jaw) movements induced by chewing gum or tobacco, eating, or talking while wearing HPDs on the job. For most earplugs the data on temporomandibular movements are limited (with the exception of slow-recovery foam plugs, which demonstrate little or no change), but large amounts of jaw movement have generally resulted in reduced protection (Abel and Rokas, 1986; Berger, 1981; Cluff, 1989). The results are even less definitive for work-related movement than for jaw movement, primarily because the activities during the experimental wearing periods have been largely unspecified. Kasden and D'Aniello (1978) reported significant losses in attenuation over a 3-hr activity period for a single-flange premolded plug (V-51R) but not for a custom-molded plug. Studies by Krutt and Mazor (1980) and Berger (1981), in which subjects wearing HPDs went about their normal office or laboratory work, demonstrated small reductions in attenuation for several earplugs of the premolded and mineral down varieties but little or no deficit for slow-recovery foam plugs. Casali and Grenell (1989) measured attenuation before and after subjects performed a light assembly task for approximately 1.25 hr while wearing Willson 665 earmuffs. A slight drop in attenuation occurred over the wearing period but only at the lowest (125 Hz) test frequency. Those studies generally pointed out that work-related and jaw movement may degrade attenuation, but none of them utilized a simulation of highly kinematic, strenuous work activity, in which hearing protector attenuation may be most likely to degrade to critical levels. Therefore, to provide a controlled, repeatable investigation of the activity variable, the HPD wearing period in this study consisted of either a vigorous, whole-body physical work activity or temporomandibular movement activity elicited by chewing movements and forced vocal efforts.

METHOD

Subjects

Forty paid volunteer subjects participated, with five males and five females randomly assigned to each of four HPD conditions. The subject group had the following characteristics:

(1) age range of 19–35 years, mean age of females = 23.1 years, of males = 24.6 years;
(2) inexperience with HPD use (less than one use every six months on average) and no prior participation in audiological experiments;
(3) no evidence of otopathic disorders, head lesions, tinnitus, or excessive cerumen in the ear canal;
(4) normal pure-tone audiogram for each ear, defined as hearing threshold levels between −10 and 20 dB at frequencies of 125–8000 Hz in octave steps (as per ANSI S12.6-1984) and determined in a screening session using a Beltone Model 114 manual audiometer.

Subjects read and signed an informed consent document indicating their willingness to participate and removed all headgear, earrings, or eyeglasses prior to the attenuation tests.

Apparatus

Attenuation test instrumentation. All REAT (real-ear attenuation at threshold) data were collected using a Békésy (1960) psychophysical procedure in which the subject pressed a control button whenever a signal was audible (causing it to decrease in 1-dB steps at an attenuator rate of 5 dB/s) and released the button whenever the signal was inaudible (causing it to increase at the same rate). In effect the subject tracked the threshold for each test frequency, producing a tracing of threshold response on a computer monitor. Using a computer scoring algorithm, the threshold for each frequency was computed as the midpoint of the series of peak and valley reversals on the tracing for each test frequency. Békésy tracings were obtained for occluded (protector worn) and unoccluded (protector off) conditions for each subject, and the difference (in dB) between the occluded and unoccluded thresholds was taken as the attenuation produced by the HPD for a given test frequency. Each time an attenuation test was taken in the experimental sequence, separate thresholds were obtained for each of nine one-third-octave noise bands, with center frequencies of 125, 250, 500, 1000, 2000, 3150, 4000, 6300, and 8000 Hz, pulsed on-off at a rate of 2 Hz (ANSI S12.6-1984). In this manner a spectrum of attenuation was determined for the HPD, as worn, for each experimental condition.

Equipment to perform these real-ear attenuation tests consisted primarily of an IBM PC/AT-controlled Norwegian-Electronics Model 828 audio signal generation, filter, and attenuator system, which presented one-third-octave band signals through four frequency response-matched loudspeakers placed at the corners of an imaginary tetrahedron surrounding the subject's head. Signals were presented in a uniform sound field around the stationary subject's head in a chamber having ambient octave-band noise levels of less than 10 dB (linear) at center frequencies from 250 to 8000 Hz and less than 24 dB at 125 Hz, and a reverberation time for all test signal frequencies less than 0.20 s. Calibration was verified daily with a Larson-Davis 800-B one-third-octave analyzer and ACO 7013 microphone. The hearing protector test facility has been verified to be in accordance with ANSI S12.6-1984 (Casali, 1988).

Work task equipment. Six simulated industrial tasks were performed by the occluded subject, who worked in a constant 28°C environment. A motorized work task similator (Figure 1) provided calibrated resistance against which the subject had to work. Using interchangeable manual control heads on the motor shaft, each of six different activities was performed during each work activity period. All activities were paced with a metronome, and physical workload was controlled using constant resistance from the simulator. These activities (with pacing in parentheses) consisted of valve turning (50 left/right half-turns per minute), ladder climbing (100 rungs per minute), crowbar work (50 push/pulls per minute), straight lever pulling (70 cycles per minute), load pushing (50 per minute), and bar (shoulder) rotation (50 rotations per minute). Concurrent with this work task, subjects were required to turn their head and neck approximately 100 deg every 5 s to monitor video displays, one located to the left and one to the right (Figure 1). This forced rapid head acceleration/deceleration, which could induce HPD slippage.

Experimental Design and Protocol

Each subject was randomly assigned to one of the four HPDs and attended four experimental sessions separated by at least 24 hr, in which one fitting procedure and one activity condition were applied in each session. A mixed-factors, complete factorial design resulted, with each HPD (a between-subjects

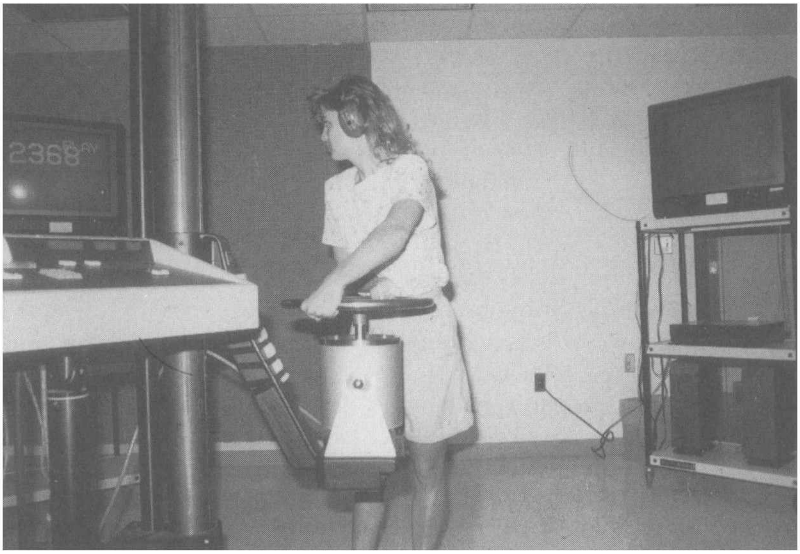

Figure 1. *An occluded subject performing a work task activity; monitoring video displays are located in the rear. Shown is the valve rotation activity, one of six activities using the Baltimore Therapeutic Equipment Work Simulator.*

variable) being donned and worn under all four combinations of fitting and activity conditions (within-subjects variables). A discussion of the levels of each independent variable follows.

HPDs. To ascertain whether certain HPDs were more susceptible than others to attenuation loss caused by fitting and wearing period variables, four diverse protector types were studied. These HPDs and their current manufacturer NRR values (laboratory-rated) are as follows:

(1) *Bilsom UF-1 Universal Earmuff* (NRR = 25 in over-the-head position): a basic foam cushion earmuff with adjustable, gimballed earcups and headband clamping force of 10.2 N at an earcup separation of 14.35 cm and head height of 13.08 cm
(2) *E-A-R Foam Plug* (NRR = 35): a cylindrical earplug made of slow-recovery foam that is finger-rolled by the user into a small-diameter cylinder, quickly inserted into the ear canal, and allowed to expand to provide a seal
(3) *E-A-R "UltraFit" Plug* (NRR = 27): a premolded polymer earplug with three hemispherical flanges of decreasing radii toward the inserted tip end (stem provided for fingertip grasp during insertion)
(4) *Combination: Bilsom muff over E-A-R foam plug* (no NRR): an exemplary combination protector for use in ambient noise levels where "double" protection is needed (no NRR is specified because the combined attenuation is less than the arithmetic sum of the individual protector attenuation).

Several examples of a third class of HPD—the ear canal cap—were tried unsuccessfully in the experiment. Most subjects complained of pain caused by localized pressure on the conchal and tragal areas of the ear and were too uncomfortable to wear the canal caps continuously for the full two-hour period. Unlike earplugs and muffs, canal caps are primarily useful for those who must go in and out of noisy areas and therefore need an intermittent use device that is easy to don and doff.

Fitting procedure. HPD fitting was accomplished under two fitting conditions, with the subject-fit condition always preceding the trained-fit condition so that the subject fit was not biased by the experimenter training. Under the subject-fit condition the subject was handed the HPD in its standard industrial packaging and asked to insert the plug (or don the muff) according to the manufacturer's printed instructions. No experimenter intervention or guidance was given, nor was the subject allowed to ask questions regarding the fitting procedures. This fitting procedure mimicked many industrial practices in which workers fit their own HPDs with no supervision. Before the attenuation tests began, subjects were allowed to adjust or refit the HPD until they were satisfied with the placement. Once fit, the subject sat quietly in the chamber for 5 min prior to the first threshold test. This allowed time for the subject to relax and become accustomed to the chamber and also for the HPD to stabilize; this was particularly important for the foam plugs, which slowly expand to conform to the ear canal.

In the trained-fit condition the subject read the manufacturer's instructions, listened to a verbal explanation of those instructions by the experimenter (without embellishment of the instructional content), and could ask questions about fitting the HPD. The experimenter provided verbal feedback while the subject practiced donning the HPD outside the test chamber but did not physically assist the subject in achieving fit. After learning the proper fitting techniques, the subject removed the HPD, entered the chamber, and replaced the HPD without the experimenter present. A 70 dB(A) pink noise was then presented so the subject could adjust or refit the HPD to subjectively block the maximum sound, as instructed by the experimenter. Once the subject was satisfied with the fit, the experiment proceeded with the stabilization period.

The rationale behind including a form of auditory feedback as a fitting aid was twofold. First, in a noisy industrial environment workers may rely on the ambient noise as an indicator of HPD seal if they become cognizant of its usefulness. For instance, earplug users may be trained to cup their hands tightly over their pinnae in the presence of noise and to listen for an increment in attenuation over that achieved with the plugs alone. If cupped hands result in subjectively quieter feedback, then a refit of the plugs may be indicated. Proper use of auditory feedback as a fitting aid may be easily attained through training, though it is not necessarily obvious to the naive user who relys only on HPD package instructions. Thus the 70 dB(A) pink noise was included only as a component of the trained-fit condition applied in this study. Second, HPD testing standards (e.g., ANSI S12.6-1984), which entail quality fit of the devices, dictate the use of noise as a fitting aid.

Wearing period and activity conditions. During each data collection session the subject performed two 30-min periods of activity outside the test chamber while continuously wearing the HPDs as originally fit. In the work activity condition, the Work Simulator movements and display monitoring task were performed for each 30-min period, with continuous activity on one of the six "jobs" for each of six 3-min work periods, separated by 2-min rest intervals. This task was highly kinematic, emphasized upper torso movements and rapid head acceleration, and induced moderate perspiration in all subjects. In the jaw movement condition the subject was seated at a desk and alternated 5-min periods of reading aloud with 5-min periods of chewing gum or eating a snack for each of the two 30-min periods. During the reading portion of the task the subject watched an analog sound level meter and tried to maintain a forced vocal effort such that the meter response to the spoken word was about 70 dB(A). This combination speaking-and-chewing task elicited almost continuous temporomandibular movement but no other physical activity during the HPD wearing period. This procedure provided a controlled means of allowing jaw movement alone to affect achieved attenuation, much as would gum-chewing or conversation in noise. The order of activity conditions was counterbalanced across subjects.

Protocol sequence for experimental sessions. First the subject was familiarized with the attenuation test and activity task procedures and practiced in Békésy threshold tracking. The subject was then audiometrically tested for temporary threshold shift as compared with the original screening audiogram; if no shift was found, the session proceeded. Pretask unoccluded (HPD off) thresholds were first obtained for each one-third-octave test band. Then using the assigned fitting condition, the subject donned the HPD and the stabilization period commenced. Once this initial fit was established, the subject was instructed *not to touch or readjust the HPD* for the remainder of the 2-hr wearing period and was continuously monitored by the experimenter to ensure compliance. Pretask occluded (HPD on) thresholds were then obtained. The subject exited the test chamber and performed the appropriate activity task for the first 30-min period. Then, following a 5-min break, the subject reentered the chamber and the first posttask occluded thresholds were established. The second 30-min task period was subsequently undertaken, followed by another short break and then the final posttask occluded threshold tests. At this juncture the HPDs had been worn for 2 hr without adjustment and attenuation data had been obtained after initial fit, after 1 hr, and again after 2 hr. The attenuation tests interspersed with the two 30-min activity periods accounted for the total 2-hr continuous wearing period. Finally, the subject removed the HPD and a posttask unoccluded threshold was obtained.

RESULTS

Threshold Data Reduction

For each experimental session and fitting of the HPD, three attenuation (i.e., noise reduction in dB) data points were computed for each of the nine test frequencies: (1) initial fit or pretask attenuation was computed as the difference between pretask occluded thresholds and pretask unoccluded thresholds at each test frequency; (2) posttask attenuation, following 2 hr of wearing, was the difference between posttask occluded and unoccluded thresholds; and (3) attenuation during the task, after 1 hr wearing, was computed as the difference between the second occluded threshold and the mean of the pretask and posttask unoccluded thresholds. The resultant data set was complete, with no missing data points attributable to HPDs falling out of the ear or subject attrition. Although none of the HPDs worked completely loose and fell off during the extended activity period, noticeable slippage did occur with approximately 20% of the subjects using the muff and with a few wearing the UltraFit earplug.

Attenuation Data Analyses

Overall analysis of variance. Mixed-factors analysis of variance (ANOVA) was applied to the complete factorial design of HPD type (H), wearing time (T), movement activity (A), and fitting procedure (F) using the dependent measure of attenuation in dB at each test frequency. All interactions of the independent variables were included in the ANOVAs. Subjects (S) were treated as a random-effects variable; wearing time, movement activity, fitting procedure, and HPD type were treated as fixed-effects variables. Complete ANOVA summary tables appear in Park (1989).

Statistically significant ($p < 0.05$) two-way interaction effects included Wearing Time × HPD at all frequencies except 8000 Hz, Fitting Procedure × HPD at all frequencies below 2000 Hz, Movement Activity × HPD at 6300 Hz, and Fitting Procedure × Wearing Time at only 500 and 6300 Hz. A three-way interaction (Fitting Procedure × Wearing Time × HPD) was significant only at 500 Hz and was analyzed and interpreted further only in the context of its significant embedded two-way effects. For the main effects significance ($p < 0.05$) was revealed for HPD type and wearing time at all frequencies, for fitting procedure at all frequencies except 6300 Hz, and for movement activity at only 3150 Hz. For each ANOVA result the data were next partitioned and analyzed with simple-effects F tests on the dimensions of interest, followed by pairwise means comparisons tests. Because of their size the F test and means comparisons test tables are not reproduced here; however, the statistically significant differences are indicated by different letters in all mean data plots. On these graphs letters do not appear with the mean values at certain frequencies, indicating that there were no statistically significant differences among the means according to the ANOVA and, therefore, that the pairs of means were not further analyzed with pairwise comparisons tests. Means for which pairwise tests were performed are labeled with letters in all cases. Unless noted otherwise, all tests were performed at $p < 0.05$.

Interaction of fitting procedure with wearing time. The presence of this interaction indicated that the fitting procedure used in initial donning of the HPD affected the stability of the device over the wearing period, but this was evidenced by attenuation reductions at only 500 and 6300 Hz. Simple-effects F tests ($F = MS_T/MS_{F \times T \times S(H)}$) on the subject- and trained-fit conditions indicated that attenuation decreased significantly over the wearing period for both fitting conditions at both test frequencies: subject fit at 500 Hz, $F(2,72) = 56.82$, $p < 0.01$; at 6300 Hz, $F(2,72) = 43.52$, $p < 0.01$; trained fit at 500 Hz, $F(2,72) = 17.20$, $p < 0.01$; at 6300 Hz, $F(2,72) = 7.91$, $p < 0.01$. However, according to pairwise Bonferroni t test results, the wearing time effect was slightly more pronounced and steady for the subject-fit condition (average reduction of 3.2 dB attenuation from pretask to posttask measurement) than for the trained-fit condition (average reduction of 1.5 dB from pretask to posttask). Under both fitting conditions the decrease in attenuation was monotonic across the three attenuation measurement junctures. These results are depicted in Figure 2.

Interaction of fitting procedure with HPD. The influence of fitting procedure on attenuation was not only time dependent but also device specific and was consistently in evidence at 1000 Hz and below in the overall ANOVA. The simple-effects F tests ($F = MS_F/MS_{F \times S(H)}$) revealed which HPDs were most sensitive to subject fit versus trained fit differences. The outcome, shown in the lower half of Table 1, was clear cut: all of the earplug HPD conditions, including the muff-plug combination, were highly susceptible to fitting procedure differences, but the earmuff was not. A post hoc comparison of mean attenuation on each individual HPD condition (except the muff) indicated that substantially lower attenuation occurred in the subject-fit condition than in the trained-fit condition, ranging from a low difference of 4.0 dB at 250 Hz for the UltraFit to a high difference of 14.1 dB at 1000 Hz for the E-A-R foam plug. As depicted in Figure 3, these fitting procedure effects were very pronounced at 1000 Hz and below for the combination, E-A-R plug, and UltraFit HPDs. Differences above 1000 Hz were apparent for the UltraFit; however, these higher frequencies were not analyzed on a post hoc basis because they lacked significance in the overall ANOVA. The upper

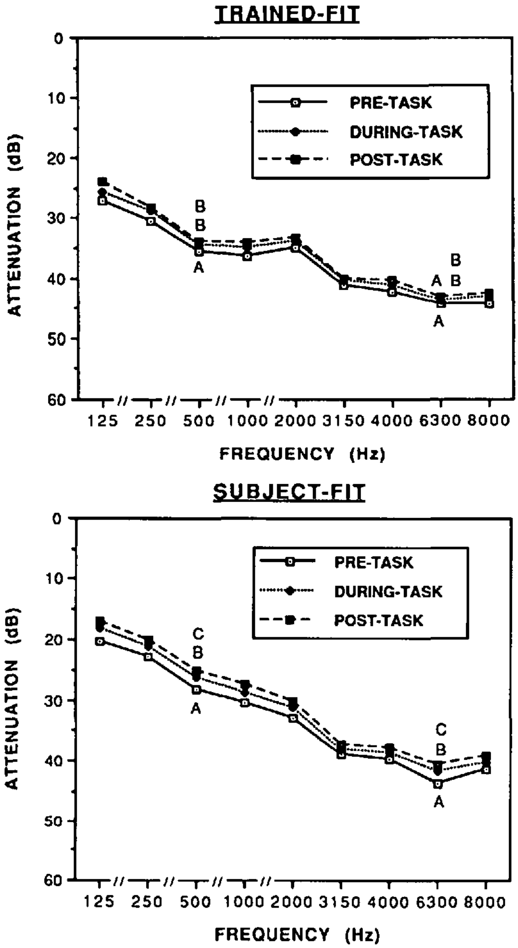

Figure 2. *One-third-octave band attenuation in dB for each fitting procedure over the course of the activity period. Means with different letters are significantly different at* $p < 0.05$ *according to a Bonferroni* t *test.*

right panel of Figure 3 clearly indicates that there was little advantage gained in protection with the earmuff when trained fitting was used instead of subject fitting according to the manufacturer's instructions alone.

Fitting procedure main effect. The fitting procedure effect, when collapsed across HPDs, demonstrated that trained fitting afforded significantly better attenuation than subject fitting at all frequencies except 6300 Hz, as borne out by the previously discussed interactions. The difference in attenuation between fitting procedures was 2–8 dB depending on frequency, with the largest differences occurring at 1000 Hz and below (Figure 4; see page 20).

Interaction of HPD with activity period. This interaction has particular bearing on HPD selection in that it revealed that changes in achieved attenuation with respect to wearing time were device specific. Based on simple-effects F tests ($F = MS_T/MS_{T \times S(H)}$) shown in the top half of Table 1, it was evident that the attenuation provided by all HPDs changed significantly over the wearing period at nearly all frequencies, with the exception of the E-A-R foam plug, which showed no attenuation changes. Subsequent Bonferroni t tests showed that except for the E-A-R foam plug there was a significant reduction from pretask protection to during-task and/or post-task protection across nearly all test frequencies (Figure 5, page 21). These reductions in attenuation were quite consistent for the UltraFit and combination protectors and less so for the Bilsom muff, for which the Bonferroni t tests revealed differences at 125, 250, 500, 2000, 4000, and 6300 Hz. When the Bilsom muff was worn over the E-A-R plug, there was a consistent decrement in spectral attenuation over the activity period which did not occur with the E-A-R plug alone and more of a decrement than occurred with the Bilsom muff alone.

Interaction of movement activity with HPD. This interaction was isolated in the ANOVA to a single frequency, 6300 Hz, and subsequent simple-effects F tests ($F = MS_A/MS_{A \times S(H)}$) were conducted to determine the differences between the two movement activities for each HPD. Only the attenuation achieved by the Bilsom muff was significantly different between activities, with more attenuation (3.4 dB) in the jaw movement condition than in the physical work activity

TABLE 1

Simple Effect *F* Test Summary Tables

Frequency (Hz)	*125*	*250*	*500*	*1000*	*2000*	*3150*	*4000*	*6300*
HPD				*F* Ratios				
F tests to determine wearing time effects for each HPD (from Wearing Time × HPD interaction)								
UltraFit plug	85.21**	19.37**	18.25**	25.38**	25.95**	11.84**	28.14**	24.28**
E-A-R plug	0.29	1.02	0.57	0.10	0.13	1.69	0.90	2.46
Bilsom muff	6.68**	6.86**	6.79**	2.71	3.75*	0.24	6.56**	3.77*
Muff/E-A-R plug	44.08**	14.41**	25.90**	20.48**	17.19**	12.04**	8.46**	14.20**
F tests to determine fitting procedure effects for each HPD (from Fitting Procedure × HPD interaction)								
UltraFit plug	9.10**	10.41**	11.89**	10.64**				
E-A-R plug	68.68**	101.87**	100.44**	98.61**				
Bilsom muff	0.12	0.54	1.05	1.28				
Muff/E-A-R plug	67.91**	113.00**	84.56**	15.68**				

* Statistically significant at $p < 0.05$; **statistically significant at $p < 0.01$.

condition, $F(1,36) = 18.83, p < 0.01$. Because this effect was restricted to a single high frequency for a single HPD, its explanation is difficult. However, it was observed that the muff appeared to slip down over the pinna more in the work activity task (perhaps because of the perspiration induced) than in the jaw movement task, in which relatively little muff slippage was evident. This could have accounted for the lower movement activity attenuation, but it is somewhat surprising that it would be evidenced only at a single high test frequency.

Activity movement and wearing time effects. Although the ANOVA indicated a significant main effect difference between jaw movement and work movement on attenuation, the difference was negligible (0.8 dB less attenuation under work activity than jaw movement) in a practical sense and occurred only at a single frequency (3150 Hz). However, the activity period did cause a significant degradation in attenuation, as revealed by the wearing time effect at all nine test frequencies (Figure 6). Bonferroni *t* analyses of this main effect revealed it to be very stable and reliable in that attenuation decreased significantly from pretask to during-task to posttask measurements at all nine test frequencies. (As discussed earlier, the magnitude of this wearing time effect was influenced by both the fitting procedure and specific HPD.) Furthermore, when the data are partitioned by specific protectors, the lack of a difference between jaw movement and work-related movement is apparent (except for the Bilsom muff), and the influence of the activity period on the spectral attenuation of all protectors except the foam plug is quite evident (Figure 5).

HPD main effect. It is well known that different types and models of HPDs widely differ in their spectral noise reduction capabilities. Therefore the presence of the main effect of protector was expected and evidenced by significant attenuation differences at all nine test frequencies. (Of course, these effects are restricted by the interactions including HPDs discussed earlier.) Results of a Newman-Keuls multiple-range analysis on mean attenuation at each frequency yielded the results shown in Figure 7. The strength of the combination muff-plug configuration is clearly evident, as is the general tendency for insert

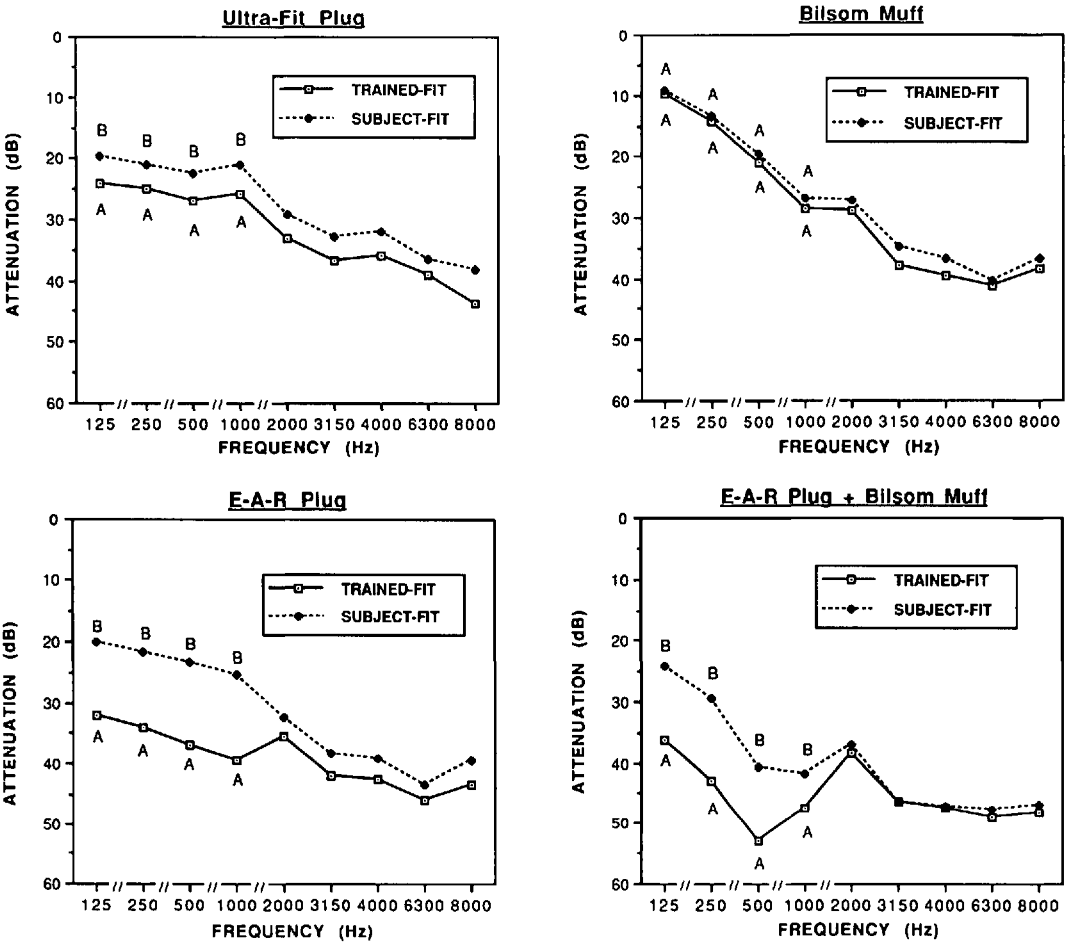

Figure 3. *One-third-octave band attenuation in dB for each HPD and fitting procedure. Means with different letters are significantly different at* $p < 0.05$ *according to a simple-effects* F *test.*

devices to yield stronger low-frequency attenuation than the muff alone.

DISCUSSION

The primary results of this experiment were that subjects' attenuation scores consistently decreased over the course of the movement activity period and were generally much poorer for the subject-fit than the trained-fit condition, though these trends were highly dependent on the particular HPD. A general discussion of these results and considerations for applying them follow.

Fitting Procedure Considerations

With the benefit of the training period to achieve better HPD fit, subjects markedly improved their achieved protection levels over those obtained when only the manufacturer's package instructions were available (i.e., the subject-fit condition). It is apparent that either the fitting information gained from the

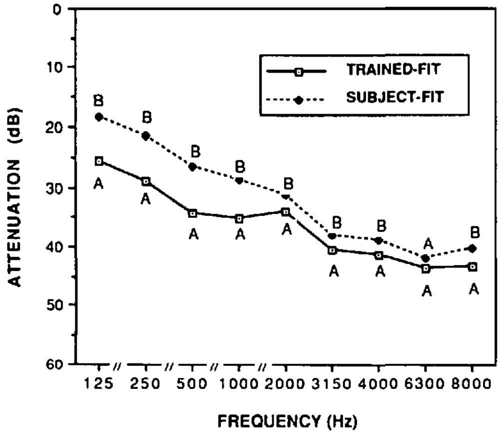

Figure 4. *One-third-octave band attenuation in dB for each fitting procedure. Means with different letters are significantly different at* $p < 0.05$.

brief interactive session with the experimenter, the use of noise as feedback for checking fit, or the combination of the two was instrumental in improving protection levels. The trained-fit condition exhibited significantly greater attenuation at eight of nine test frequencies, and the protection benefit was most pronounced (ranging from 6.5 to 8 dB at ≤1000 Hz) when attenuation loss caused by poor fit would be most evident (Figure 4). However, the advantage of fit training was highly HPD specific, especially in that the muff showed negligible improvements in attenuation when training was utilized (Figure 3). Perhaps this was because this muff was quite straightforward to don, especially when compared with some formable insert devices that must be molded by the subject prior to insertion. Of the two plugs in the sample, the user-molded foam plug was reported by subjects to be more difficult to insert than the premolded polymer plug, largely because of the need to roll, compress, and quickly insert it before it returned to its original shape. This was borne out by the larger low frequency (≤1000 Hz) attenuation differences (ranging from 11.9 to 14.1 dB) between subject-fit and trained-fit conditions for the foam plug than the comparable low frequency differences (4.0 to 4.7 dB) for the polymer plug (Figure 3). The foam plug's sensitivity to user training was also evident in the attenuation plots for the combination protector, with the same pattern of fitting procedure influence at 1000 Hz and below as in the individual foam plug graph (Figure 3).

In general, muffs may be easier to don and less susceptible to the influence of user training than are insert devices (Casali and Epps, 1986; Casali and Lam, 1986). However, this is not necessarily true for all varieties of muffs, some of which require more complex headband and earcup adjustments than others. With most earplugs it is especially important to note the particular instruction that the pinna of the ear should be pulled upward and slightly outward to straighten the ear canal prior to plug insertion. Without such knowledge many individuals will obtain an inadequate noise seal resulting from too shallow an insertion, and inadequate protection may result. Not only may air leaks occur, but because less of the earplug contacts the canal walls, the resulting lower stiffness and reduction in effective mass may compromise attenuation. This is generally borne out in this study by the decreases in low frequency attenuation in which the effects of airborne transmission and HPD vibration would likely be most apparent.

Although it occurred at only two test frequencies, the interaction of fitting procedure with wearing time implies that training a subject to properly fit an HPD may aid its stability during vigorous movement over an extended wearing period. Readjustment of a properly fit HPD under workplace conditions may be undesirable for hygiene reasons. This is less critical for earmuffs, which can easily be readjusted without touching the ear, than

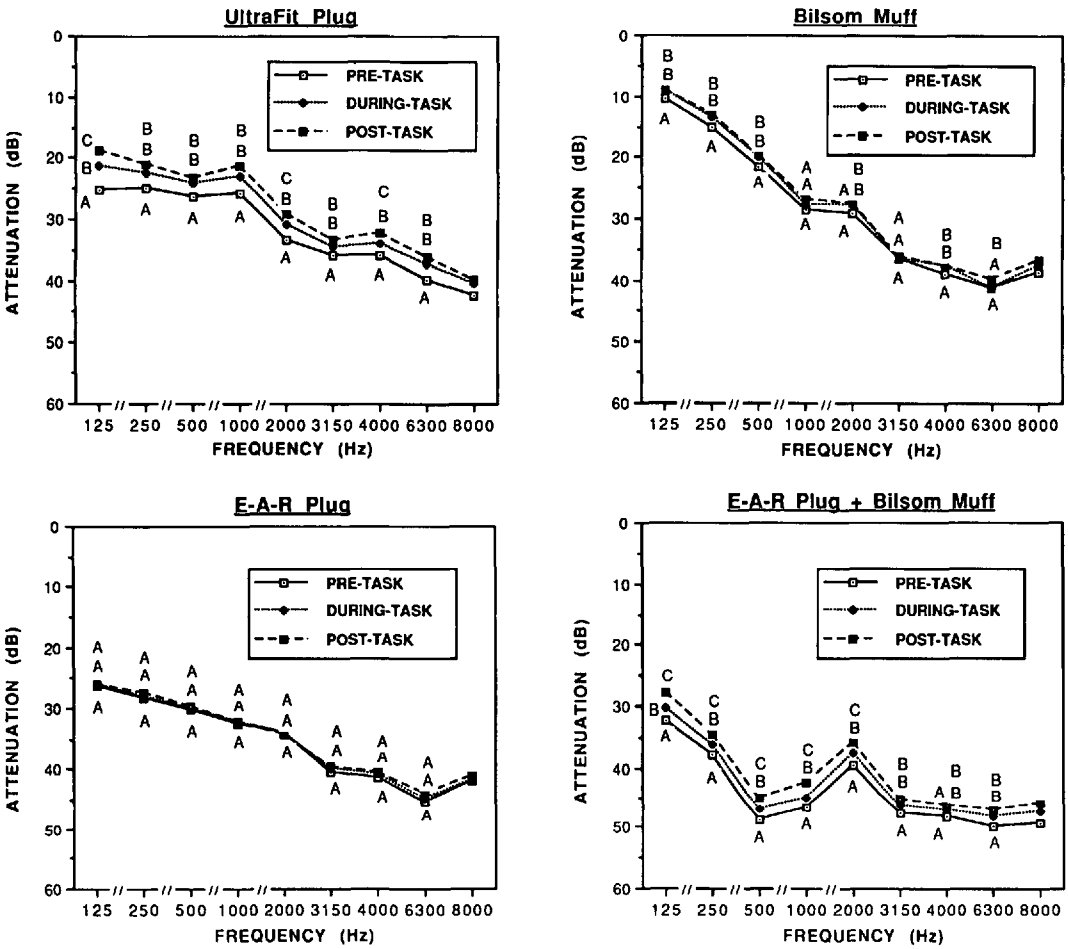

Figure 5. *One-third-octave band attenuation in dB for each HPD over the course of the activity period. Means with different letters are significantly different at* $p < 0.05$ *according to a Bonferroni* t *test.*

for earplugs, which may work loose and require reinsertion in the workplace using soiled hands.

Wearing Time and Movement Activity Considerations

The reduction in attenuation over the wearing period clearly indicated the tendency of certain protectors to loosen under working or jaw-movement conditions (Figure 5). The UltraFit plug exhibited the largest drop over the 2-hr period, with a reduction of nearly 4 dB in average protection afforded. The average attenuation of the muff-plug combination deteriorated by approximately 3 dB, which was slightly more than the combined reduction in attenuation of the foam plug and muff alone. Not only was the attenuation of the Bilsom muff resilient to fitting procedure effects, it also was only slightly affected by the activity period. The pretask to posttask attenuation losses were largest at 500 Hz and below, in-

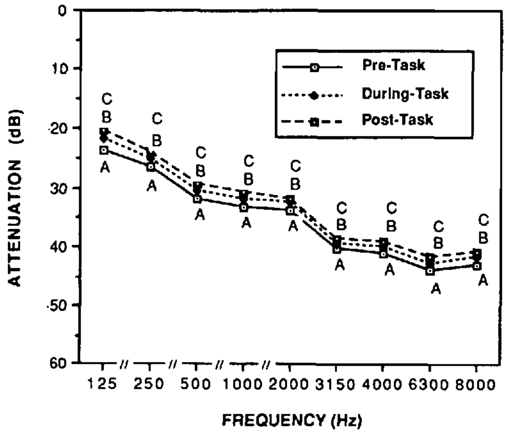

Figure 6. *One-third-octave band attenuation in dB over the course of the activity period. Means with different letters are significantly different at* p < *0.05 according to a Bonferroni* t *test.*

dicating the possibility of loss of muff cushion seal, but were small (about 2 dB). With reference to the type of movement activity, the Bilsom muff was the only HPD that demonstrated an attenuation difference between activities, but this was evidenced at only 6300 Hz. It may be that the rapid accelerations caused by head turning and the perspiration induced by the work activity were more critical to repositioning of the muff than to the insert protectors, though the UltraFit did exhibit some slippage. Jaw movement, however, had little effect on the earmuff's protection performance.

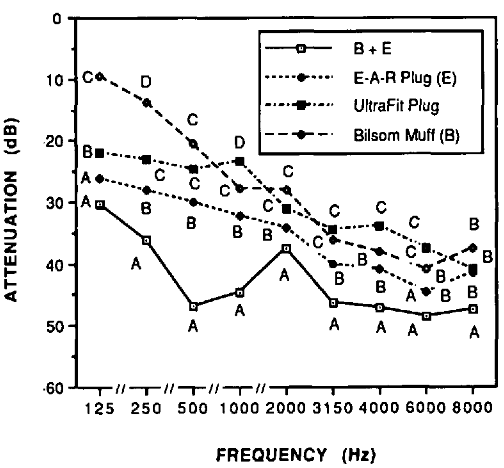

Figure 7. *One-third-octave band attenuation in dB for each HPD. Means with different letters are significantly different at* p < *0.05 according to a Newman-Keuls test.*

The E-A-R foam earplug was most resistant to wearing time effects over the movement tasks. This is another example of an HPD-specific effect, in that the foam plug was the most susceptible of the sample to attenuation improvement attributable to user training and the least susceptible to attenuation losses resulting from user activity. Its inherent porous texture (which helps to develop friction with the canal walls) and compliance with canal distortions may be responsible for the plug's stability of fit under the vigorous jaw and work-related movements.

Overall Protection Performance with the Different HPDs

The frequency-specific attenuation achieved with the HPDs in this study, when collapsed across the levels of the other dependent variables, provides a reasonable indication of average performance for several fitting and usage conditions. However, before the data are generalized to the field setting, a validation experiment must be performed to determine the adjustments necessary to the data set to provide field protection predictions.

It is evident in Figure 7 that the premolded UltraFit earplug (manufacturer's NRR = 27) and the Bilsom muff (manufacturer's NRR = 25) yielded similar overall protection, with the plug exhibiting a 9-dB or more advantage at the lower frequencies of 125 and 250 Hz and the muff, a 3-dB or more advantage at 4000 and 6300 Hz. In industrial practice it is sometimes assumed that muffs offer better attenuation than do plugs, but, as borne out by these data, this is not necessarily the case. If there is an advantage to muffs it will usually occur at higher frequencies, whereas some plugs are better at the low end of the noise spectrum, as indicated in this study.

Of the three single-protector configurations, the slow-recovery foam earplug consistently produced the highest attenuation values across all frequencies except 4000 Hz and above, where it was not significantly better than the muff (Figure 7). When this plug was combined with the muff, attenuation increased significantly over that of the plug alone at 500 Hz (by 16.7 dB), 1000 Hz (by 12.3 dB), 250 Hz (by 8.3 dB), 3150 and 4000 Hz (by 6.4 dB), and 8000 Hz (by 6 dB). Considering the muff attenuation alone, the protection improvement gained by adding the plug was even more dramatic and was significant at all nine frequencies, with attenuation increments ranging from 8 dB at 6300 Hz to 26 dB at 500 Hz. Clearly the combination HPD configuration offers considerably greater protection than that of the single devices, though the combined attenuation values are always less than the sum of the individual HPD attenuations. The theoretical limit of any HPD's attenuation is the user's bone conduction threshold at that frequency, because the bone conduction pathway to the inner ear flanks the HPD's primary defense against noise—that is, interruption of the air conduction pathway. In fact, the presence of the HPD may actually lower the bone conduction threshold from that found in open-ear conditions, and the magnitude of this effect depends on the particular device and how it is fit (Casali, 1989). In general the combined protector attenuation in this study approaches the bone conduction threshold at 2000 Hz and above when compared with the results of Berger (1983b). Therefore, this configuration appears to provide near-optimal protection even when the attenuation data are collapsed across the dynamic usage conditions in this study. A muff-plug combination may be necessary for very high noise exposure conditions, but there is some disadvantage to "overprotection" if speech communications are needlessly hampered by the high attenuation.

In light of the demonstrated influences of fitting procedure and movement activity period, a comparison of the realistic protection performance of the four HPD configurations must depend on these and, perhaps, other factors. The apparent advantage of one HPD over another may be either negated or improved under certain fitting or dynamic usage conditions that occur in the workplace but not in the typical laboratory test.

CONCLUSIONS

The following implications are supported by the results of this study.

(1) With poor protector fit and/or during vigorous wearer activity there is risk of compromised hearing protection and perhaps OSHA regulation noncompliance. Proper device selection and user training may help to ensure that adequate protection occurs. Double protection (muff over plug) provides an added margin of safety and may be indicated for very high ambient noise environments.

(2) Standard laboratory protocols (e.g., ANSI S12.6-1984) for obtaining estimates of HPD attenuation and subsequent rating of devices require revision if realistic influences on protection levels are to be considered. Attenuation values obtained immediately following an experimenter-supervised fit of the HPD, as in the standard practice, overestimate actual HPD performance (Berger, 1983a). Furthermore, both subject fitting of the HPD using only the package instructions and movement activity over a 2-hr wearing period caused noteworthy reductions in attenuation for most of the devices investigated in this study. Both of these conditions are common to industrial, military, or general use of HPDs and, as demonstrated herein, can be reproduced in a laboratory setting for testing purposes. If such protocols can be made

standard and repeatable across laboratories, they may demonstrate utility in providing more realistic estimates of HPD field performance. However, prior to this application a field validation is required.

(3) Because of their differential susceptibility to movement effects, HPDs must be carefully screened and selected for application in highly dynamic, kinematic situations such as heavy industrial materials handling tasks or high-g acceleration environments. Muffs may be more prone to slippage and loss of seal caused by head or body movements and/or perspiration than are some earplugs, but they have the advantage of quick, easy, and hygienic readjustment. It appears that slow-recovery foam earplugs exhibit a resiliency to attenuation loss resulting from head/torso movements or vigorous temporomandibular activity and, if fit properly, may offer reliable protection levels in tasks involving such movements.

(4) The substantial improvements in protection levels for the foam, premolded, and combination muff-plug HPDs achieved with brief training of the subject (as compared with subject fit with the package instructions) underscore the need to instruct HPD users in initial device fit and also in device readjustment during work. If certain HPDs are known to work loose, as demonstrated in the tasks studied here, the user must become cognizant of the loss in seal and learn to readjust the HPD to maintain adequate protection levels. Furthermore, it is critical that package instructions be conspicuous, easy to understand, and convey a logical, proper method for donning the HPD. Although training seminars, videotapes, and other supplementary materials are available to augment the training of HPD use, in many cases package instructions are the sole information on which the user relies. With this in mind, and also considering that a trained-fit condition (as investigated herein) is not the typical industrial practice, there is considerable merit in working toward new standards for testing HPDs and their associated instructions as an integrated system—that is, using naive subjects donning the protectors with only the package instructions as a guide. This would closely mimic the typical fitting scenario for the new employee given HPDs for the first time for use on the job.

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