An Exploratory Study of Moderate Physical Activity and Selected Design Attribute Effects on Earmuff Attenuation

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Hearing protection devices are tested for their attenuation characteristics under controlled laboratory conditions. Unfortunately, these tests overestimate the typical attenuation performance of the devices in the field, posing the possibility of inadequate protection for the user. Many factors may affect achieved in-field attenuation. This research investigated the influence of the user's work-related movement and variations in headband compression force and earcup cushion material (liquid- or foam-filled) on the frequency-specific noise attenuation achieved with earmuffs. Real-ear attenuation at threshold (REAT) testing procedures were used to collect attenuation data on 24 subjects both prior to and following completion of a simulated work task. Statistical analyses indicated that moderate work-related movement significantly decreased low-frequency attenuation but by only a small amount (1.5 dB at 125 Hz). A high headband compression force was found to increase attenuation by approximately 1.5 to 4 dB at 125, 250, 500, and 8000 Hz. There was no significant difference at any frequency between cushion types. The results indicate a small effect of moderate physical work activity on hearing protector effectiveness and illustrate the importance of certain earmuff design parameters to achieved attenuation.

Background

Laboratory-obtained spectral attenuation data and EPA-required[1] noise reduction ratings (NRRs) estimate the noise protection achievable with an optimally-fitted hearing protection device (HPD) used by trained and motivated users. NRRs probably are not an accurate indication of the protection provided in actual workplace use.[2] Many work-related factors and problems associated with HPD use are excluded from the laboratory test. These include workers' physical activities, perspiration, prolonged use (compared to the short duration of laboratory tests), interference with HPD sealing (such as by eyeglasses), improper HPD fit, irregular use because of induced discomfort, and employee alteration of the devices.[3-6] Several studies have addressed various aspects of the discrepancy between in-workplace performance and laboratory ratings of HPD effectiveness.[3,4,7-12] In general, in-workplace (or simulated in-workplace) attenuation exhibits consistently lower mean values with higher variance than corresponding laboratory-obtained attenuation for a given HPD.

Although previous research has identified work-related factors that can limit HPD effectiveness, rarely has the magnitude of their influence on attenuation been subjected to controlled study. There is a definite need to determine the effects of on-the-job influences, such as workers' physical activities, on attenuation. Furthermore, while the relationship between certain HPD design attributes (e.g., earmuff cup volume) and attenuation has been well defined on a purely physical basis,[13] relatively little attention has been given to the behavioral effects on this relationship, which determine the HPD's practical performance as it is worn and used. Also, the interaction of design attributes and work-related influences has not been addressed.

The primary objectives of this exploratory study were to investigate (1) the effects of variations in the earmuff design attributes of headband compression force and earcup cushion material (foam and liquid filled); (2) the effects of moderate work-related physical activity over a 75-min wearing period; and (3) the relationship between the design attributes and the earmuff's susceptibility to attenuation loss caused by the physical activity.

Headband compression and cushion type were investigated since, through the use of interchangeable parts for a common earmuff model, their levels could be manipulated in isolation, with minimal effect on other attributes, such as size, overall weight, and earcup volume. In addition, since these attributes readily are changed in earmuff development and fabrication practice, information relevant to their design should be of practical use to manufacturers. Higher compression forces should result in improved attenuation through the creation of a better seal against the head.[13,14] Since air leaks maximally affect low frequency attenuation,[13,15] it is at these frequencies that differences in attenuation caused by changes in compression force would be expected most. The expected effects of foam- versus liquid-filled cushion types on attenuation are somewhat ambiguous, with liquid cushions expected to provide slightly greater attenuation at low frequencies and foam slightly more at high frequencies.[14]

For the physical activity variable, by pacing the subject's movements in the laboratory and holding constant other attenuation-influencing factors, the effect of moderate work activity could be investigated. It can be hypothesized that enough movement will reduce low frequency attenuation by causing the HPD to shift, resulting in air leaks. Movement effects also may interact with earmuff design features in influencing attenuation. For instance, tighter headbands likely will increase an earmuff's stability in the face of physical movement. Therefore, for jobs requiring considerable worker movement and exertion, a higher compression earmuff may be indicated.

Experimental Materials and Methods

Subjects

Paid volunteer subjects (12 males, 12 females) participated. Subjects had no prior experience with earmuff-type hearing protectors, no otological problems, and no beards, long sideburns, or eyeglasses. As specified by ANSI S12.6-1984,[16] subjects were accepted if their mean threshold level, for each ear, was no better than -10 dB and no worse than 20 dB at seven pure-tone test frequencies in octave steps from 125 Hz to 8000 Hz.

Experimental Facility and Instrumentation

All earmuff attenuation tests were performed in a 2.8 × 1.9 × 2.4 m test chamber using 1/3 octave-band test stimuli in a diffuse sound field and utilizing the threshold determination procedures specified in ANSI S12.6-1984.[16] Details of this facility, a part of the Auditory Systems Laboratory at Virginia Tech, appear elsewhere.[17,18]

Experimental Design

The mixed, four-factor experimental design included the within-subjects variables of headband compression, work-related activity, and test frequency, and the between-subjects factor of cushion type. During each of three experimental sessions, the subject donned a Willson 665 earmuff (Reading, Pa.) (Figure 1) comprised of the assigned cushion type and one of the three headbands. The subject was tested for unoccluded and occluded thresholds at all nine test frequencies, both prior to and following a series of work-related activities. Each cell of the experimental design was blocked with 6 males and 6 females. A brief discussion of each independent variable follows.

Headband Compression

Compression forces of the headbands were measured at an earcup separation of 14.35 cm (5.65 in.).[16] The mean compression forces were 24.4 N (high), 16.1 N (medium), and 14.4 N (low). (The terms high, medium, and low were not intended to describe subjectively the "feeling of compression" induced by the headbands; instead they were used only for identification purposes.) The medium and low headbands were standard plastic production units, while the high compression headband was a glass-fiber reinforced plastic unit. The four units of each headband were measured once in combination with each cushion type, and the average of the

Figure 1—Willson 665 earmuff worn by all subjects.

eight measurements was reported as the mean compression for the headband.

For each headband compression force/cushion type combination, the area of cushion contact with the user's head was measured at an earcup separation of 14.35 cm (5.65 in.) so that the pressure exerted against the head could be computed for each earmuff configuration. The contact pressures were determined to be 8743 Pa, 5773 Pa, and 5342 Pa for the liquid cushions with the high, medium, and low compression headbands, respectively. In the same order, the contact pressures for the foam cushions were 8540 Pa, 5787 Pa, and 5237 Pa.

To isolate the effect of compression force, all other headband design features (width, method of adjustment, etc.) were constant between headbands. Furthermore, with the exception of the earcup cushion, all other earmuff design features (earcup liner, size, etc.) were constant between headbands. The four units of each headband were rotated equally throughout the study. Furthermore, to reduce possible order effects, presentation of the three compression forces was according to two identical balanced Latin square designs.

Earcup Cushion Material

Both the liquid and foam-filled cushions were enclosed in black vinyl covers. Other than the filler material, all cushion design features (diameter, thickness, etc.) were constant between cushion types. The only exception was a small weight difference between the foam (185 g) and liquid (220 g) cushion earmuffs, to which subjects did not appear sensitive.

Work-Related Activity

During each experimental session, attenuation values were obtained both prior to and following completion of a simulated work task. The task was designed to lead the subjects through controlled and time-paced head and body movements—including limited walking and talking, reaching, stooping, twisting, sitting, and standing—similar to those commonly found in a light industrial sorting/assembly task at a sit-stand work station. The task was not strenuous and did not require sustained muscular exertion. Subjects verbally responded to taped queries and identified part numbers aloud during performance of the task. A more detailed task description is presented elsewhere.[17]

Initial Attenuation Assessment

First, instructions were given for all experimental procedures, and the subject practiced the work activity task. After being seated in the chamber, the subject was familiarized with the psychophysical procedures and given practice on the threshold determination test. The subject's unoccluded thresholds then were established using the method of limits, with three threshold trials at each test frequency.

Next, the experimenter instructed the subject in the proper fitting technique, and the subject applied the earmuff according to an "experimenter-supervised" fitting procedure.[16] A 70-dBA broadband noise was introduced, and the subject was instructed to adjust the protector carefully to eliminate as much noise as possible. The experimenter then rechecked the earmuff fit, calling for a refit if necessary. Once proper fit was obtained, the subject was told not to touch the earmuff. The subject's initial occluded threshold then was determined over three trials, using the same protocol as for the unoc-
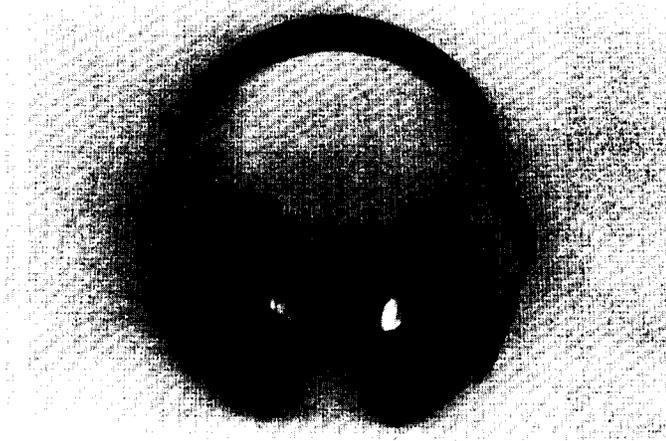
cluded test. For each frequency the difference between the mean of the three initial occluded trial thresholds and the mean of the three unoccluded trial thresholds was taken as the pretask attenuation provided by the protector. It was not possible to pair each unoccluded and occluded trial in succession because once the earmuff was donned, it could not be removed until after experimental task completion and posttask occluded threshold measurement.

The subject rated the earmuff's comfort and acceptability 25 min after the earmuff fit was first obtained (and shortly following the pretask occluded test). These comfort data are presented elsewhere.[17]

Performance of Experimental Task

After the ratings, the subject began the simulated work task. Subjects who completed the task within 20 min remained seated until the work activity period was over. At all times, subjects wore the earmuffs as originally fitted and were prohibited from touching or adjusting them.

Second Attenuation Assessment

After the task was concluded, exactly 50 min from the original earmuff fitting and first pretask occluded trial, the subject's second occluded threshold was determined. In all, the earmuff was worn, as originally fitted, for 75 min. All movement and speech in the interim period was limited to that elicited by the work task, which was highly controlled and paced.

Following a short break, the earmuff was removed and a second unoccluded threshold assessment was made. As before, the difference between the posttask mean occluded threshold and posttask mean unoccluded threshold at each frequency constituted a measure of the earmuff's postactivity attenuation.

Finally, the earmuff was refit according to the experimenter-supervised procedure, and another occluded threshold determination was made. These data were compared against the pretask mean occluded thresholds to ascertain if differences in attenuation were introduced by practice, fatigue, or the varying order of presentation of the occluded and unoccluded trials. The mean thresholds of the pretask occluded and posttask refit occluded threshold assessments were compared using a t-test. This test revealed no significant differences, $t(142) = 0.32$, $p = 0.75$, so the pretask values were used in the subsequent data analyses.

Results

Overall Frequency-Specific ANOVA

First, a mixed-factors analysis of variance (ANOVA) was performed on the mean attenuation data. Statistically significant ($p < 0.05$) differences were found for the headband compression (H), subject work-related activity (A), and test frequency (F) main effects, but not for cushion type (C) and gender (G). The HxF, AxF, FxC, FxG, and HxFxC interactions also were found to be significant. Because attenuation data collapsed linearly across frequencies are of little value, the main effects were not analyzed further. Instead, the interactions of the independent variables of interest with test frequency were scrutinized further with post-hoc analyses. Attenuation means and standard deviations for each of these

interactions are plotted in the figures below along with a letter coding for the statistically significant differences revealed.

Headband Compression x Frequency Interaction

This significant interaction effect, $F(16,320) = 4.89$; $p = 0.0001$, demonstrated that the mean attenuation (collapsed across subject activity and cushion type) associated with each of the headbands varied significantly across test frequencies. To distinguish between the attenuation values associated with the three headbands at each individual frequency, the data at each test frequency were subjected to a Fisher test[19] conducted at an error rate of 0.01. As depicted in Figure 2, small but significant differences were revealed at 125, 250, and 8000 Hz where the high compression headband offered significantly greater (by 2–4 dB) mean attenuation than either of the other headbands, and at 500 Hz, where the mean attenuation associated with the high compression headband was greater (by 1.5 dB) than with the low compression headband. At no frequency was a significant difference between the medium and low compression headbands demonstrated, possibly because of the relatively small force difference (1.7 N) between them.

In general, the data seem to indicate that while headband compression did affect attenuation significantly at low frequencies, small variations in compression force are not likely to result in great differences in attenuation for this particular earmuff. More data are needed, however, before this relationship is understood fully and prior to recommending critical compression values. In particular, this study investigated only three compression forces, one of which (24.4 N) is probably at or near the upper limit of tolerance for extended wearing periods. Information on lower compression forces and on forces which lie between the medium and high values in this study is needed also. Furthermore, the interaction between compression force and cushion deformation against the head, which results in pressure distributed around the
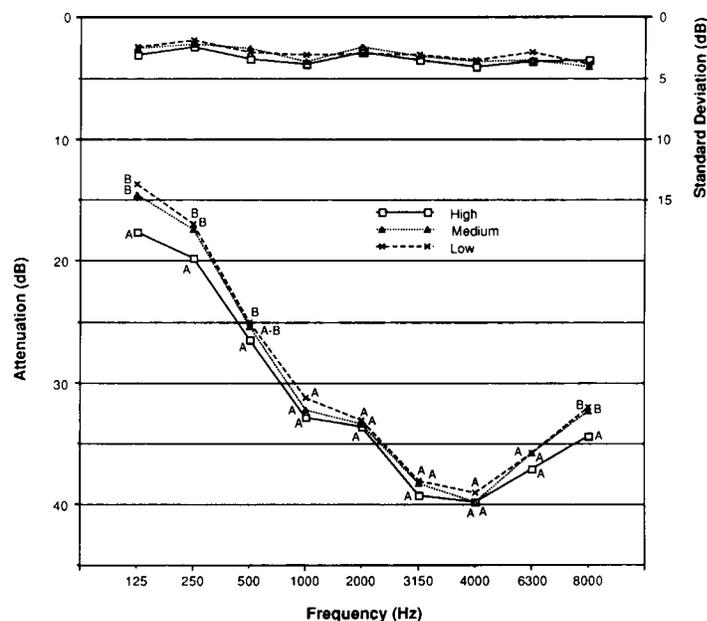

Figure 2—Attenuation associated with each headband compression force across test frequencies. (Means with different letters are significantly different at $p < 0.01$.)

pinna (or perhaps peak pressure loads on some spots), requires further study.[20]

Cushion Type x Frequency Interaction

Attenuation values associated with each cushion type varied significantly across test frequency, $F(8,160)$ = 7.59; p = 0.0001. Bonferroni t-tests[19] were selected to accomplish nine frequency comparisons between cushion types to offer conservative protection from the inflated error rate problem associated with making many multiple comparisons. A family-wise error rate of 9% was selected, resulting in a per-comparison error rate of 0.01. Differences were found at 125 Hz, where the foam cushion offered significantly greater attenuation ($p < 0.001$), and at 500 and 1000 Hz, where the liquid-filled cushion offered significantly more noise reduction ($p < 0.001$), as depicted in Figure 3.

Work-Related Activity x Frequency Interaction

The overall ANOVA revealed this interaction to be significant at $F(8,16)$ = 3.87; p = 0.0003. To isolate differences between the pre- and postactivity attenuation values on a by-frequency basis, pairwise comparisons within this interaction were conducted again at each frequency using Bonferroni t-tests, at $p < 0.01$. As depicted in Figure 4, the only frequency at which there was a statistically significant loss in attenuation between pre- and posttask conditions was 125 Hz, and this difference was small. Overall, it must be concluded that for the earmuffs tested, the level of subject's work-related activity had little effect on attenuation except at the lowest frequency.

The fact that low frequency attenuation was reduced slightly by subject activity was expected since the movements likely caused the earmuffs to shift, creating air leaks (which are most detrimental to low frequency attenuation) between the sealing cushion and the side of the head. These results suggest that perhaps more strenuous and kinetic activity might cause greater reductions in attenuation, particularly at low frequencies.
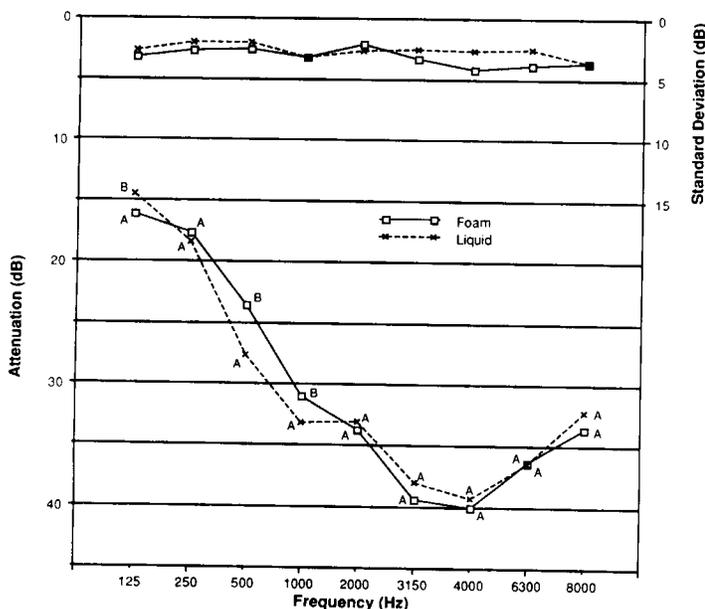

Figure 3—Attenuation associated with foam and liquid cushions across test frequencies. (Means with different letters are significantly different at $p < 0.01$.)
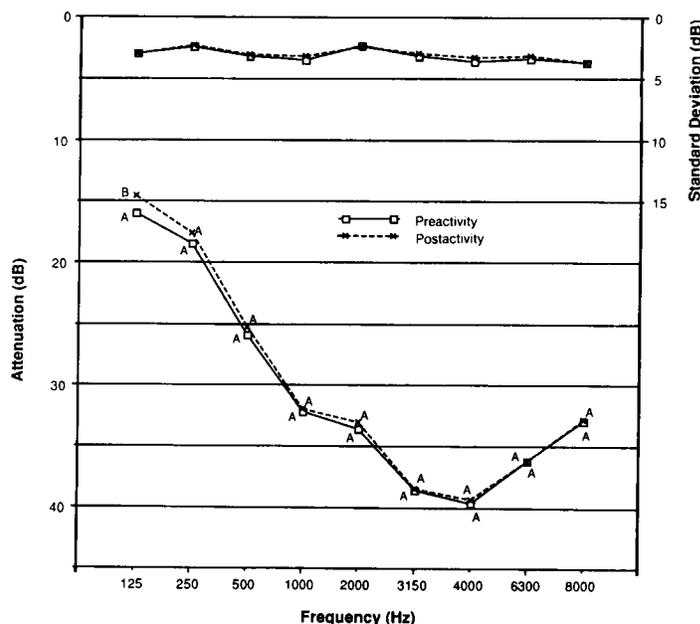

Figure 4—Attenuation associated with pre- and postactivity conditions across test frequencies. (Means with different letters are significantly different at $p < 0.01$.)

Gender x Frequency Interaction

Having yielded a significant ANOVA effect, $F(8,160)$ = 2.49; p = 0.014, the mean attenuations by gender for each frequency were analyzed further and plotted in Figure 5. The Bonferroni t-test analysis ($p < 0.01$) revealed differences at only two test frequencies: females received greater protection than males at 500 Hz, and the genders reversed at 4000 Hz, for no clear reason.

Secondary Analysis on Noise Reduction Rating Data

Despite the fact that many other factors require consideration (e.g., fit, comfort, durability, user acceptance), judgments and comparisons of HPDs often are made primarily on the basis of laboratory-obtained attenuation data. To simplify these frequency-specific data for use in making comparisons and computing an employee's noise exposure while wearing the device (and, therefore, determining compliance with OSHA noise exposure regulations), the data are collapsed into a single number rating of the protector's attenuation capabilities, the Environmental Protection Agency (EPA) noise reduction rating (NRR).[1] The NRR is of considerable practical importance to manufacturers, purchasers, and users of earmuffs, and it greatly (perhaps overly) simplifies the interpretation of HPD attenuation data.

NRR Calculations

NRR values were computed for each of the 12 combinations of headband compression, cushion type, and subject activity, as reported in Table I. Each NRR was computed from the frequency-specific attenuation data collected on 12 subjects (6 males, 6 females), with 3 occluded and 3 unoccluded trials for each, resulting in 36 attenuation trials in all. In computing the NRR, it was necessary to match (pairwise) the first preactivity unoccluded trial with the first preactivity occluded trial, and so on, to determine the attenuation associated with each trial.
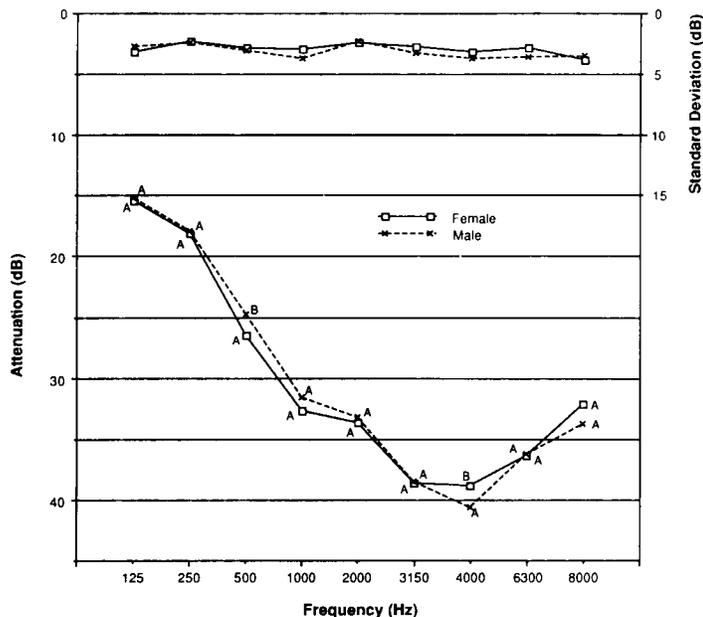
Figure 5—Attenuation by gender across test frequencies. (Means with different letters are significantly different at $p < 0.01$.)

By collapsing attenuation data across subjects and across the nine test frequencies to compute the NRR, only one observation remained in each cell of the reduced experimental design. This precluded any further statistical analysis of the NRR data. It may be observed, however, that with the exception of the medium compression headband/foam cushion combination, all earmuffs exhibited a decrease in NRR between the pre- and postactivity conditions, corroborating the frequency-specific results discussed previously.

Discussion

The primary objective of this study, to explore the potential effects of moderate work-related physical activity over an extended wearing period on earmuff attenuation, was met. Although small in magnitude, a statistically significant reduction in achieved attenuation was found from pretask to posttask measurements, but only at 125 Hz. In addition, differences in attenuation caused by variations in headband compression were found, with the high compression headband exhibiting the highest attenuation, particularly at low frequencies. Another objective, however, to ascertain the relationship between design attributes and an earmuff's susceptibility to losses in attenuation caused by the work-related factors, was unfulfilled. This was evidenced by the lack of any significant interaction between the subject activity and earmuff design variables. The ensuing discussion focuses on the results of the study as they pertain to these objectives and offers suggestions for further research.

Effect of Work-Related Factors on Earmuff Attenuation

Examination of the results (e.g., Figure 4) suggests that sufficient work-related activity may reduce the amount of attenuation achieved with earmuffs. It should be noted that the activities and movements required to complete the simulated work task were not highly violent nor strenuous and

did not induce perspiration which may enhance earmuff slippage. The task was intended to be representative of what might be required of workers employed in a repetitive light assembly or sorting job. In addition, longer periods of earmuff use than the 1 hr and 15 min period in this study are common. Therefore, while the influence of the wearing period and simulated work activities on attenuation appears to be small, its potential importance should not be ignored. In fact, the effect of wearing time and work-related activities well may be job specific.

Furthermore, the effect of these factors on an earmuff's effectiveness may be compounded if the device is improperly fit or applied. For example, an earmuff which is worn over eyeglasses or with a welding hood may be more susceptible to influence from work-related movement. Given the abundance of improper HPD fitting techniques which are common in industrial use,[10,12] this possibility deserves careful consideration.

Effects of Headband Compression and Cushion Type on Attenuation

As expected, it was demonstrated that headband compression force directly influences earmuff attenuation, particularly at low frequencies. The greater attenuation realized with the high compression headband likely is attributable to its improvement of the cushion seal against the side of the user's head. The elimination of air leaks is critical to noise attenuation, especially at low frequencies. These results coincide with the fact that considerable differences in force existed between the high compression force and the low or medium forces (10.0 N and 8.3 N, respectively), while the difference between the two lower forces was comparatively small (1.7 N). Thus, based on the results with this earmuff, it appears that small differences in compression force may not greatly affect achieved attenuation. Further efforts are needed to assess a more complete continuum of compression forces, however, with smaller intervals between adjacent levels, to determine the optimal design range.

Unless extreme noise levels mandate maximal protection, the benefits of higher compression force should be weighed against the possible negative influence that this attribute

TABLE I
Noise Reduction Ratings (NRRs) for each of the 12 Earmuff/Work Activity Conditions

Headband Compression	Cushion Type	Activity	NRR
High	liquid	pre-	24.1
High	liquid	post-	23.0
Medium	liquid	pre-	23.2
Medium	liquid	post-	22.6
Low	liquid	pre-	22.3
Low	liquid	post-	21.8
High	foam	pre-	22.1
High	foam	post-	21.8
Medium	foam	pre-	20.1
Medium	foam	post-	20.3
Low	foam	pre-	21.2
Low	foam	post-	21.1

may have on user comfort and acceptability. Although earmuffs typically are manufactured as universal-fit devices, variability in head sizes (height and width) and shapes leads to differences in the amount of compression force exerted by an earmuff. Thus, an individual's head dimensions and the headband compression force should be considered as concomitant influences on attenuation and on user comfort. Also, based on these results, the choice between foam and liquid cushions appears to be a matter of personal preference and is somewhat dependent on such nonattenuation factors as comfort, acceptability, and compatibility with the environment of use.

Future Research Directions

Further research investigating the effects of work-related activities and prolonged wearing time on earmuff, earplug, and canal cap attenuation is needed. In particular the influence of different levels of physical activity—ranging from the type of moderate activities utilized in the present study to strenuous, physically-demanding activities—needs to be examined. With longer wearing periods than the 75-min period in this study, attenuation should be measured at several intervals to track the influence of different lengths of physical activity.

The relationship between earmuff design attributes and an earmuff's susceptibility to work-related influences also needs to be explored further. More loss in attenuation in fact may occur with more violent physical movement and higher muscular force exertions, with lower headband compressions, or with other earcup cushion models. Furthermore, the relationship between physical activity and attenuation losses needs to be established for additional earmuff design attributes (e.g., weight) and for different HPD types, such as inserts and canal caps.

Through the proper application of such human factors research, the variables which influence hearing protector attenuation and comfort may be understood better. Thus, hearing protector design may benefit and testing procedures may improve, ultimately resulting in more effective hearing conservation for industrial personnel.

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