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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 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.

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 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 re-

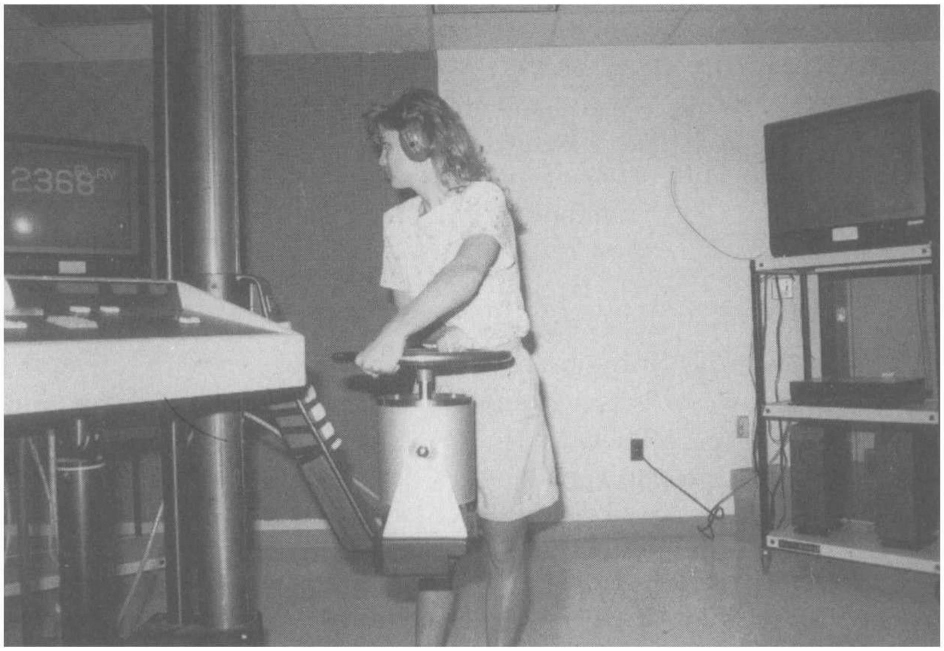

Figure 1. *An occluded subject performing a work task activity; monitoring video displays are located in the rear. Shown is the valve rotation activity, one of six activities using the Baltimore Therapeutic Equipment Work Simulator.*

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 pre-molded 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

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