Passive Augmentations in Hearing Protection Technology Circa 2010 including Flat-Attenuation, Passive Level-Dependent, Passive Wave Resonance, Passive Adjustable Attenuation, and Adjustable-Fit Devices: Review of Design, Testing, and Research

John G. Casali

Auditory Systems Laboratory, Grado Department of Industrial and Systems Engineering, Virginia Tech, Blacksburg, VA 24061

(Received 9 March 2010; accepted 9 June 2010)

Augmentations or enhancements to conventional HPDs, that is, those which attenuate noise strictly through static, passive means, are generally delineated into passive (non-electronic) and active (powered electronic) designs. While powered electronic augmentations are reviewed in Casali[1] (a parallel paper elsewhere in this issue), passive augmentations are represented by mechanical networks to achieve flat-by-frequency attenuation; level-dependent leakage pathways that house acoustically-variable occluders to yield minimal attenuation during quiet periods but sharply increasing attenuation upon intense noise bursts (such as gunfire); quarter-wave resonance ducts to bolster attenuation of specific frequencies; selectable cartridges or valves that enable passive attenuation to be adjusted for specific exposure needs; and dynamically adjustable-fit devices that provide adjustment features to enable personalized fit to the user as well as some degree of attenuation control. Intended benefits of passive augmented HPDs (akin to those of active devices as well) include (1) more natural hearing for the user, (2) improved speech communications and signal detection, (3) reduced noise-induced annoyance, (4) improved military tactics, stealth maintenance and gunfire protection, and (5) provision of protection that is tailored for the user's needs, noise exposure, and/or job requirements. This paper provides a technical overview of passive augmented HPDs that were available or have been prototyped circa early-2010. In cases where no empirical research results on the passive augmentations and their performance were available in the research literature, this review relied on patents, corporate literature, and/or the author's experience. For certain augmentations, a limited amount of empirical, operational performance research was available and it is covered herein. Finally, in view that at the juncture of this article the United States (U.S.) Environmental Protection Agency (EPA) was in the process of promulgating a comprehensive new federal law to govern the testing and labeling of hearing protectors of various types, those elements of the proposed law that pertain only to specific passive augmentation technologies are mentioned herein,[2] along with references to relevant standards on hearing protector attenuation testing.

1. INTRODUCTION

An overview of the state of the technology of hearing protection devices (HPDs) circa 1996 was published by Casali and Berger.[3] Considering that article is now outdated by 15 years, the purposes of this review are (1) to update the earlier article with coverage of new technology augmentations, specifically on available *passive* technologies, (but not exhaustively in regard to all manufacturers/models), (2) briefly present the results of relevant research conducted on passive augmented HPDs, and (3) to briefly cover the testing and labeling of passive augmented HPDs as to their attenuation and other performance characteristics under a recently proposed U.S. EPA regulation[2] that is intended to ultimately supercede the current federal regulation,[4] which does not accommodate most augmentation technologies, be they passive or active. The testing issue was not addressed in the earlier article,[3] but it is becoming increasingly important as consumers and safety professionals attempt to select from a variety of augmented HPDs. These HPDs are purported to offer certain hearing and protective advantages, but heretofore they could not be comprehensively tested and properly labeled under the current EPA regulation, for reasons associated with the nonapplicability of the EPA's cited test protocols[4] to certain dynamic HPD capabilities, as reviewed elsewhere.[5]

1.1. Definitions Applied

In this paper and its parallel paper,[1] the terms "augmentation" and "augmented hearing protector" are intended to refer to any device that does not consist solely of a static passive attenuator, but which includes features involving electronics or dynamic/adjustable passive acoustical impedance elements. Also, the term "active" hearing protector is operationally defined as one which incorporates powered electronics of any type, which are typically powered from a battery source. Herein, the term "active" does not refer exclusively to devices of the active noise reduction type, or of the active sound transmission/restoration type, but instead it encompasses both of these varieties since they include powered electronics design features.

1.2. Conventional Passive Hearing Protection Devices (HPDs) and Applications Thereof

The bulk of available HPDs comprise the category of so-called conventional devices. These devices are the subject of numerous reviews (e.g., see Gerges and Casali[6]) The parallel paper[1] provides a discussion of the primary characteristics of conventional passive HPDs, which reduce noise at the ear solely by static (i.e., invariant) passive means, yield attenuation behavior that is noise level-independent or amplitude-insensitive and which, at least in most examples, provide nonlinear, increasing levels of attenuation as spectral frequency increases (see Fig. 1 in Casali[1]). At the time of this writing, conventional HPDs are tested under the prevailing EPA regulation,[4] using a real-ear attenuation at threshold (REAT) standard (ANSI S3.19-1974; Experimenter-Fit Method[7]); soon to be replaced by ANSI S12.6-2008[8] in the EPA's newly proposed rule,[2] as discussed in Casali.[1]

A major stimulus for the development of augmented HPDs has been the sometimes negative influence that conventional HPDs have on the hearing ability of users.[9, 10] These issues, including the effects of conventional HPDs on auditory perception, reduced speech communication abilities, and degraded signal detection, recognition, and/or localization, are reviewed in the parallel paper[1], as well as in other publications,[9, 10] and will not be repeated here. Furthermore, the reader is referred to Casali[1] for a variety of reasons that HPDs are applied to noise annoyance and hazard problems, including laws pertaining to occupational noise exposures.[11, 12]

The overview in Casali[1] about the effects that conventional HPDs have on the hearing of speech and signals concludes that these effects are sometimes deleterious to auditory performance and situational awareness, as do other references.[9, 10] Thus, these effects have largely given rise to the passive augmentations to HPDs that are discussed herein, and to the active (electronic) augmentations that are covered in Casali.[1] Relying upon empirical research evidence where available, herein the operational performance for each passive HPD augmentation technology will be discussed along with the basic design features and approaches for each individual technology.

1.3. Hearing Protection Device Attenuation Measurement Methods and Related Standards

Prior to addressing each augmentation technology on an individual basis, the reader is referred to the parallel article,[1] in which an overview of the measurement techniques that are now used, or anticipated to be used for obtaining an HPD's attenuation performance, and the product labeling therefrom, is presented. This background information is prerequisite to understanding how the proposed new U.S. EPA product noise labeling regulation[2] for HPDs will accommodate the testing for each passive augmentation technology.[1] The parallel article[1] covers the three major standardized HPD measurement techniques that apply to the testing of various aspects of augmented passive technologies discussed herein, and yielding appropriate attenuation data. These include Real-Ear Attenuation at Threshold (REAT) as detailed elsewhere[13, 14] and standardized in ANSI S12.6-2008,[8] Microphone in Real-Ear (MIRE) as detailed elsewhere[13, 14] and standardized in ANSI S12.42-2010,[15] and Acoustical Test Fixture techniques, as cited in ANSI S12.42-2010[15] with actual fixtures/manikins appearing under separate standards as referenced in Casali.[1] It is important to reiterate here that in the EPA's recently proposed rule,[2] for a REAT test per ANSI S12.6-2008[8] is required for all types of HPDs as a basis for labeling the *passive attenuation* of the device. Then depending upon the particular augmentation involved, other MIRE or ATF tests are also required for other components of attenuation, all as detailed in Casali.[1] In addition to a discussion of the EPA product noise labeling regulation[2] and the associated American National Standards Institute (ANSI) HPD test standards on which it relies, the parallel article[1] also provides reference to International Organization for Standardization (ISO) standards that cover hearing protector testing.

2. OVERVIEW OF PASSIVE AUGMENTED HPDS: DESIGN, TESTING, AND RESEARCH

2.1. A New Classification Scheme

Casali and Berger's 1996 classification scheme for augmented hearing protectors used a dichotomy of passive (non-electronic) and active (electronic) devices, with augmentation categories under each.[3] That dichotomy remains today, but due to advances in the 15 years since the original classification, a new augmentation classification appears in Table 1 of the parallel paper in this issue.[1] Next, each augmentation in the passive category will be addressed separately.

2.2. Passive Uniform Attenuation HPDs

Conventional HPDs do not improve the speech/noise (S/N) ratio in a given frequency band, and S/N is the most important factor for achieving reliable detection or intelligibility.[9] As a general trend, and especially so for earmuffs, conventional HPDs do attenuate high-frequency sound more than low-frequency sound, thereby reducing the power of consonant sounds that are important for word discrimination and which lie in the higher frequency range.[9] The sloping, nonlinear attenuation profile versus frequency, which provides higher attenuation values with increasing frequency, creates an spectral imbalance from the listener's perspective. This imbalance occurs because the relative amplitudes of different frequencies are heard differently than they would be without the conventional HPD, and thus broadband acoustic signals are heard as spectrally different from normal; in other words, they sound more bassy.[3] Thus, the spectral quality of a sound is altered, and sound interpretation, which is important in certain aural tasks, may suffer as a result. This is one of the reasons that uniform (or flat) attenuation HPDs have been developed as an augmentation technology, since these devices do not bias, on a relative basis, the hearing of sounds across the audible frequency range.

It is generally evident that on average across conventional HPDs, earmuffs display a larger imbalance between their low- and high-frequency attenuation than do earplugs.[6] However, some earplugs demonstrate substantial spectral nonlinearities in their attenuation, as shown in the two lowermost functions of Fig. 1. When listening to a sound while wearing such conventional earplugs (or an earmuff), all pitches that compose the sound are reduced in level, but due to the influence of the nonlinear attenuation, the amplitudes of various pitches are also changed relative to one another in a nonuniform manner across the spectrum, rendering the wearer's hearing of the sound as distorted when compared to its perception with the unoccluded ear. Since many auditory cues depend on their spectral shape for informational content (e.g., pitch perception by musicians,

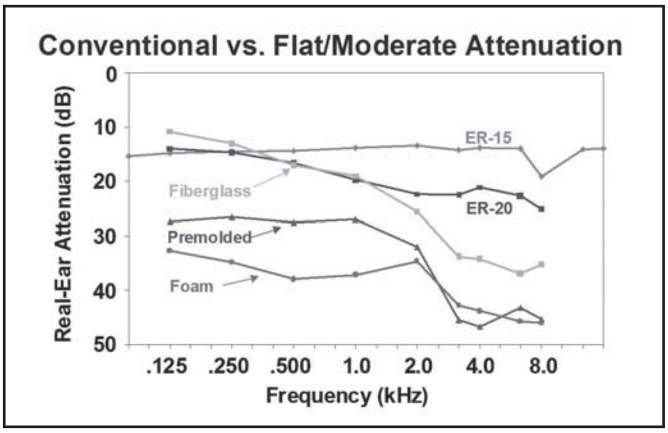

Figure 1. Spectral attenuation obtained with REAT procedures for the two uniform attenuation, custom-molded earplugs (ER-15, ER-20) that are depicted in Fig. 2, compared with three conventional earplugs shown: premolded, user-molded foam, and spun fiberglass. [Courtesy of AEARO-3M Corporation.]

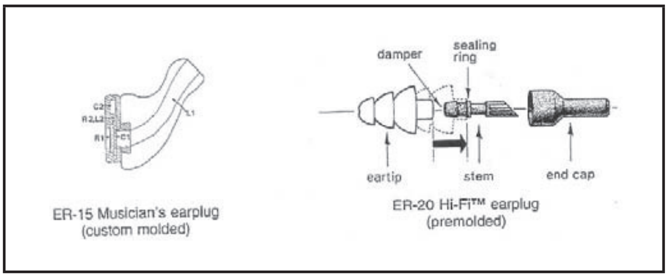

Figure 2. Flat-attenuation earplugs with controlled passive leakage pathways and acoustical networks of the custom-molded and premolded varieties.[3]

cutting speed/friction by machinists, impending bearing failures by helicopter pilots, "roof talk" by underground miners), conventional HPDs may compromise these cues.[9,10]

In an attempt to counter these effects, flat- or uniform-attenuation HPDs, such as the Etymotic ER-15 Musician's custom-molded earplug or the ER-20 HiFi™ premolded earplug, both available from AEARO-3M and Etymotic Research, Inc., were developed in the early 1990s.[3] These devices utilize acoustical damping and filtering networks (Fig. 2), as well as unique placement of the sound entry port near the ear canal's rim, to provide essentially flat attenuation over the range of frequencies from 125 Hz to 8000 Hz as shown in the uppermost functions of Fig. 1

2.2.1. Research on Passive Uniform Attenuation HPDs

Due to the simple fact that a uniform HPD's relatively flat attenuation spectrum enables the listener's ears to retain their normal, albeit uniformly attenuated, frequency response, perceptual advantages of these specialized hearing protectors are obvious, and for certain user populations, such as musicians, the more natural hearing provided should prove to be beneficial. However, the purported benefits to hearing perception of flat attenuation HPDs have been tested in few studies. One notable exception was a demonstration experiment by Witt, who, in an effort to determine whether the presence of flat attenuation was noticeable by HPD users in industrial applications, recorded speech and industrial noise under varying attenuation slopes of earplugs and played them back to obtain subjects' responses.[16] The benefits of near-flat attenuation (as achieved with a prototype of the Sperian AirSoft™ earplug) were most noticeable in industrial settings when the increase in earplug attenuation was less than a slope of 10 dB over the frequency range of 250 Hz to 4000 Hz. Furthermore, Witt noted that while the first flat attenuation devices developed in the 1990s (i.e., the ER earplugs discussed above) utilized controlled, tuned leakage paths and dynamic mechanical networks to yield their linear attenuation, advances in earplug materials in the first half of the 2000s decade have enabled near-linear attenuation in certain disposable earplugs, thus bringing the cost of uniform (or at least "near-uniform") attenuation technology down into the realm of more industrial users.[16] To achieve near-uniform attenuation with such disposable devices, however, the quality of fit is important, since an acoustical leak will invariably degrade the low-frequency attenuation. It is also important to recognize that "true" flat attenuation HPDs (i.e., ER-15, ER-20) that incorporate the leakage paths and mechanical networks noted above provide generally lower attenuation than that afforded by most well-designed conventional earplugs, so they are not typically appropriate for ear defense in high exposure levels.[3,9]

Alali and Casali[17] recently evaluated normal hearers' abilities to localize a vehicle reverse (backup) alarm, in 360-degrees azimuth in a hemi-anechoic space, comparing the subjects' performances while they wore each of the following HPDs: (1) sound transmission earmuff (Impact™ by Sperian) of dichotic design (two unique microphones, one feeding each ear cup), (2) sound transmission earmuff (custom-made) of diotic design (single microphone feeding both ear cups), (3) uniform attenuation earplug (ER-20 Hi-Fi™ by AEARO-3M), (4) level-dependent earplug (Arc™ by AEARO-3M), (5) conventional premolded 3-flange earplug (UltraFit™ by AEARO-3M), (6) conventional foam earplug (SparkPlug™ by Moldex), and (7) conventional passive earmuff (Leightning™ by Sperian). Additionally, the subjects were also evaluated in an unprotected ear condition.[17] A "quiet" condition of an A-weighted pink noise level of 60 dB and a "construction noise level" condition of an A-weighted pink noise level of 90 dB were applied, as well as both standard and spectrally-widened (with the addition of 400 Hz and 4000 Hz components) backup alarms. Subjects indicated the angular direction of the approaching backup alarm with an azimuth computer pointer. More details on this experiment appear in section 4.3 of the parallel paper.[1]

In regard to passive augmented HPD effects in the Alali and Casali localization experiment, there was not a statistically-significant advantage for either the standard or modified backup alarm on any of the four measures of localization accuracy for the ER-20 HiFi™ uniform attenuation earplug as compared to any of the other four passive HPDs, with three exceptions.[17] These exceptions, as depicted in Fig. 3, were that in percentage correct localization in an A-weighted pink noise level of 90 dB, the uniform earplug yielded significantly better accuracy than the polyurethane, user-molded foam earplug (Moldex SparkPlug™), the dichotic, electronically-modulated sound transmission earmuff (Bilsom Impact™), and the custom-made, diotic, electronically-modulated earmuff. There was no significant improvement of the uniform earplug over the standard premolded earplug, that is, the AEARO UltraFit™, which incorporates the exact same flanged seal design as the uniform earplug. Also notable was that in the high noise level condition (an A-weighted noise level of 90 dB) none of the four passive earplugs showed any disadvantage in localization accuracy when compared with the open ear (Fig. 3).[17]

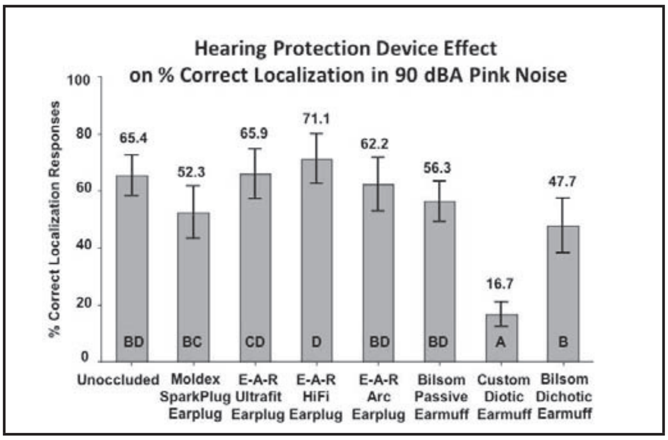

Figure 3. Effect of hearing protection device type on the percentage of correct localization accuracy for vehicular backup alarms, normal hearing listeners in an A-weighted pink noise level of 90 dB. Localization was scored as correct when the subject identified the alarm as coming from within a range of 22.5 degrees on either side of the alarm's exact angle of approach. (Mean values with 95% confidence limits shown; HPD means with the same letter are not significantly different at $p < 0.05$).[17]

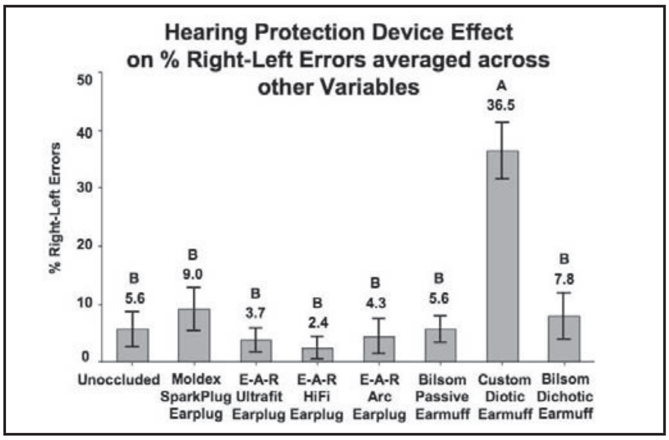

Figure 4. Effect of hearing protection device type on the percentage of right-left errors for vehicular backup alarms, normal hearing listeners in pink noise, averaged across A-weighted noise conditions of 60 dB and 90 dB, and across a standard and modified backup alarm (see text for explanation). An error occurred when an alarm that emanated from within an angle of ±45 degrees from directly to the right of the subject was judged as coming from the left, and vice-versa. (Mean values with 95% confidence limits shown; HPD means with the same letter are not significantly different at $p < 0.05$).[17]

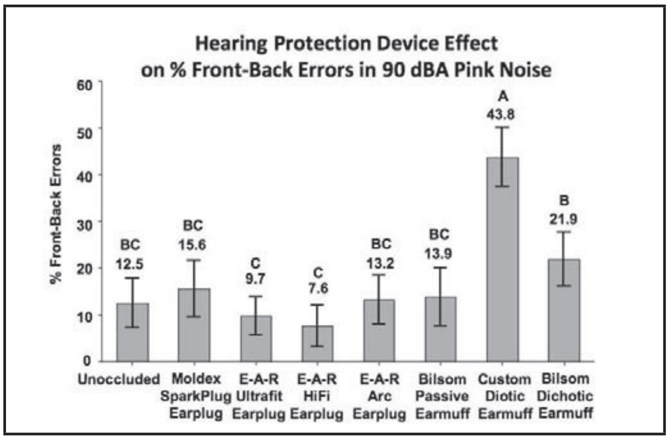

Figure 5. Effect of hearing protection device type on the percentage of front-back errors for vehicular backup alarms, normal hearing listeners in an A-weighted pink noise level of 90 dB. An error occurred when an alarm that emanated from within an angle of ±45 degrees from directly in front of the subject was judged as coming from the rear, and vice-versa. (Mean values with 95% confidence limits shown; HPD means with the same letter are not significantly different at $p < 0.05$).[17]

A comparison of the effects on symmetrical direction judgment confusions while using the uniform attenuation earplugs compared with the other HPDs is also needed.[17] In regard to right-left errors (averaged across both backup alarms and both noise levels), there were no significant differences between any of the HPDs, except for the diotic earmuff, which was associated with 37% right-left confusion errors compared to a low of 2% for the uniform HiFi^{TM} earplug to 9% for the Sparkplug^{TM} foam earplug (Fig. 4).[17] Confusions of front-back alarm directions were most significant in the A-weighted noise level of 90 dB condition (Fig. 5). The UltraFit^{TM} and HiFi^{TM} earplugs exhibited significantly fewer front-back confusions than either of the electronic muffs (Fig. 5). Among the four earplugs, the conventional earmuff, and the open ear, there were no differences in front-back errors, though the uniform attenuation HiFi^{TM} earplug did have the numerically lowest confusions at 8%, compared to a high of 16% for the conventional Sparkplug^{TM} foam earplug. Based on the composite findings of this localization study, it appears that the uniform attenuation qualities of a moderate-attenuation HiFi^{TM} earplug have certain advantages over some other earplugs, as well as over electronic sound-transmission earmuffs, in providing for localization to a backup alarm; however, it must be recognized that this conclusion is based on an experiment with specific independent variable conditions, and thus the results may not be generalizable to other signals, noises, or HPDs.

2.2.2. Testing of Passive Uniform Attenuation HPDs

Because the passive uniform attenuation HPDs devices discussed under this category all provide the same level of noise attenuation regardless of noise level (i.e., they are level-independent), their attenuation testing is accommodated in the EPA proposed rule[2] by standard REAT tests, namely those of ANSI S12.6-2008,[8] and their attenuation labeling will be based on that test, and structured per that rule's requirements for the "primary label" for the Noise Reduction Rating (NRR) for passive HPDs.[2] (The current EPA rule[4] requires the NRR appear on a label accompanying the HPD, and it is intended to estimate the protection achievable by 98% of the population; however, at this juncture it is expected that the NRR will likely change to a two-number NRR-like rating to provide a range of percentiles in the EPA's newly proposed rule.[2] Thus, for simplicity it is referred to as 'NRR' in the remainder of this paper.)

2.3. Passive Level-Dependent (Amplitude-Sensitive) Devices

Passive, level-dependent HPDs are designed so that their attenuation increases as the ambient noise level increases. Such devices rely upon acoustical networks, mechanical ball or flutter valves, or orifices in blocked sound ports which respond dynamically to intense air pressure changes to activate their unique attenuation responses. One of the earliest designs in this category was a unique dynamically-valved earplug named the Gunfender^{TM},[18] and the North Safety Co. followed with a device called the Sonic Ear-Valve^{TM}. In the early 1990s, an additional earmuff style device that relied on a sharp-edged, orifice-based, controlled leakage path in a duct was E·A·R Corporation's Ultra 9000^{TM}.[19] Later, using similar technology comprising a calibrated leaky filter in an acoustical duct

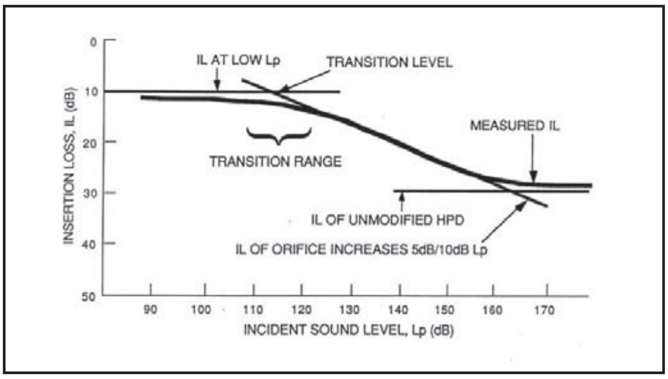

Figure 6. Representative insertion loss (IL) and illustration of the transition level at a single frequency, as a function of incident sound level (L_p), for an amplitude-sensitive hearing protector with a nonlinear orifice.[19]

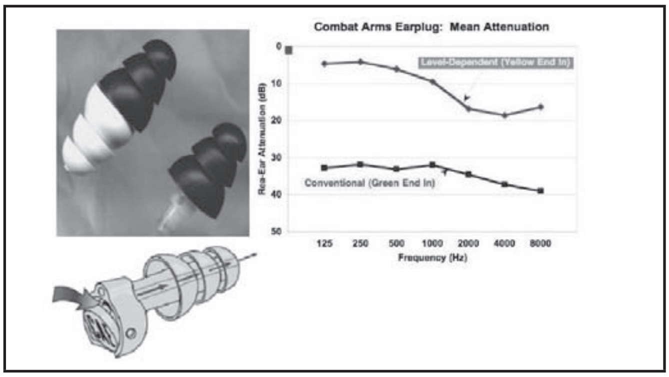

Figure 7. Combat Arms^{TM} earplug. Left panel: first generation double-ended earplug, consisting of green end (non-level-dependent) for insertion during continuous noise exposures, and yellow end for insertion where hearing is needed during quiet but gunfire may occur; on right, with yellow flange removed, revealing ported stem which contains an orifice-filter network that penetrates the duct's occluding member, for effecting level-dependent attenuation when yellow end is inserted.[20] Right panel: Combat Arms^{TM} double-ended earplug attenuation: Lower function-green end (non-level-dependent); Upper function-yellow end (level-dependent), with attenuation measured in "resting" state. [Courtesy of E. H. Berger, AEARO-3M Corporation, personal communication, January 12, 2004.] Lower left figure-third generation Combat Arms^{TM} single-ended earplug with rocker valve to change attenuation state, shown in level-dependent position.

running through the stem of an earplug, the AEARO Combat Arms^{TM} earplug was developed for military use, which was followed by a recent commercial version named the Arc^{TM} earplug.[20,21] Recently, a European custom-molded earplug was introduced, the Variphone Stopgun^{TM}, which uses a nonlinear filter to attenuate impulsive noises of above about 110 dB, according to the manufacturer's website.[26] Typically, passive level-dependent HPDs provide very low attenuation in low to moderate noise levels; however, as ambient noise levels increase to a certain level, their attenuation increases to the maximum and plateaus afterwards (Fig. 6).[3,19]

With contemporary orifice/acoustical filter-based, level-dependent HPDs at low noise levels, their passive attenuation behaves as that of a leaky protector, offering minimal attenuation below about 1000 Hz because laminar flow is present in the duct and sound passes with low impedance through the orifice. This minimal attenuation is all that is available to protect the wearer's hearing at sound levels below about 110 dB. Since such devices are intended to be used primarily in intermittent impulsive noise, this should not be a problem as long as the off periods are relatively quiet (e.g., below an A-weighted noise level of approximately 85 dB). At elevated sound pressure levels (above about 110 dB to 120 dB, as might occur during a gunshot), the flow through the orifice changes from laminar to turbulent, effectively closing the orifice and thus sharply increasing the attenuation of the device (Fig. 6).[19] Due to the fact that level-dependent earplugs of the Combat Arms^{TM} and Arc^{TM} types provide very little protection at sound levels below an A-weighted noise level of about 110 dB (with an NRR of 0 dB; spectral attenuation in right panel of Fig. 7), they are clearly not suitable for continuous noise exposures and are intended for intermittent exposures which entail quiet periods interrupted by sudden explosions, gunshots, arc blasts, high-pressure pneumatic discharges, or similar impulsive sounds. However, to provide protection in situations wherein both intermittent quiet/impulsive noise as well as periods of continuous noise can manifest, both the Combat Arms^{TM} and Arc^{TM} earplugs were designed with two "ends" that afford selectable protective states, in which one end is level-dependent, and the other is a conventional passive earplug that is suitable for continuous noise exposures.[20,21] (Now in its third generation, a more recent version of the Combat Arms^{TM} earplug incorporates a single end that is manually converted between the two aforementioned conventional and level-dependent states by a manually-operated, rocker-activated valve.) Figure 7 depicts the level-dependent and conventional passive ends of the original Combat Arms^{TM} earplug (which is still available), the spectral attenuation for each of the two ends, and the more recent single end configuration. An additional advantage is that some orifice-based, level-dependent HPDs, an example being the AEARO-3M Ultra 9000 earmuff^{TM},[19] offer roughly flat attenuation, though this is not the case with the level-dependent end of the Combat Arms^{TM} earplug, as shown in the upper spectral attenuation function of Fig. 7.

2.3.1. Research on Passive Level-Dependent HPDs

It should be obvious that passive level-dependent HPD designs are intended to provide improved auditory performance and situational awareness in quiet conditions, especially for military personnel. However, research to examine the operational performance effectiveness with these devices has been limited, even though a few application-oriented experiments have been reported, all investigating the Combat Arms^{TM} or similar Arc^{TM} earplug. Babeu et al.[20] performed laboratory experimentation leading to a report that the yellow, level-dependent end of the Combat Arms^{TM} provided better sound (azimuth) localization in noise and in quiet than an AEARO-3M Classic^{TM} foam earplug, but not better than the Combat Arms^{TM} earplug's conventional passive triple-flanged end (which is essentially an AEARO-3M Ultrafit^{TM} design).[20] In the aforementioned backup alarm localization investigation by Alali and Casali, the industrial version of the Combat Arms^{TM} earplug (the Arc^{TM}), when worn with its level-dependent end in an A-weighted noise level of 90 dB, did not result in improved localization over the conventional Ultrafit^{TM} earplug, though it did exhibit a 10%, though statistically-nonsignificant, improvement over the Moldex SparkPlug^{TM} foam earplug (Fig. 3).[17]

In a military field training experiment conducted by Casali et al.[21] with actual soldiers in scouting and raid exercises that required auditory-before-visual detection of an enemy camp, the level-dependent end of the Combat Arms^{TM} earplug resulted in auditory detection of the camp at 46 meters, compared to considerably longer (i.e., earlier) detection distances

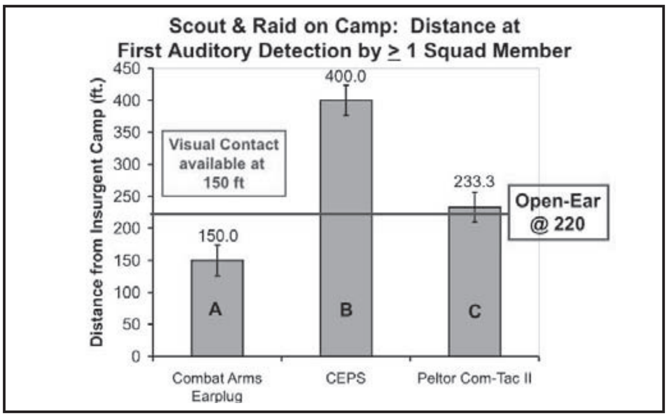

Figure 8. Mean enemy camp auditory detection distances in an Army field training exercise, with one level-dependent earplug (Combat Arms^{TM}) and two TCAPS (described in text), compared to the open ear. (Mean values with 95% confidence limits shown; HPD means with the same letter are not significantly different at $p < 0.05$.)[21]

with electronic tactical communications and protection systems (TCAPS) of 122 meters with a communication enhancement and protection system (CEPS) ear insert (which has about 36 dB gain), and 71 meters with a Peltor Comtac II^{TM} earmuff (which has about 15 dB gain), all compared to 67 meters with the open ear (Fig. 8).[21] Soldiers also reported on post-exercise questionnaires that, compared to open ear listening, even though they could still hear some signals and quietly whisper while wearing the level-dependent end of the Combat Arms^{TM} earplug, they felt that their hearing was compromised to the point that they might miss threats that they could normally detect with open ears, and that the earplug affected their ability to modulate their own voice level, likely a manifestation of the "occlusion effect".[9,21] The occlusion effect results from an enhancement of bone and tissue conduction of sound, as compared to that occurring with the open ear that is caused by occlusion of the ear canal by an earplug or earmuff. The effect is maximized as the entrapped volume of the ear canal is at its largest, such as with a shallowly inserted earplug, and it causes one's own voice to sound louder and sometimes more bassy and resonant. Also, sounds of bodily origin, such as breathing and footfalls, are heard as unnaturally loud.[9,21]

Finally, another study by Babeu was aimed at determining the protective effectiveness of the Combat Arms^{TM} earplug as worn under an infantry soldier's helmet (Model PASGT) to gunfire produced from an M4 carbine (rifle).[22] This study demonstrated that the level-dependent end of the Combat Arms^{TM} yielded a protected peak pressure level of 133 dB and insertion loss of 31 dB, compared to 120 dB and 34 dB, respectively, for the conventional end. By comparison, the unprotected, open-ear condition (but still wearing the helmet) yielded a peak pressure of 164 dB and an insertion loss of 0 dB.[22]

2.3.2. Testing of Passive Level-Dependent HPDs

Because passive level-dependent devices are now tested under the current EPA rule,[4] which only requires REAT protocol that is performed at the listeners' threshold of hearing per ANSI S3.19-1974,[7] the attenuation data are valid only for the devices' performance in quiet. As such, the NRR is very low, for example, 0 dB for the original Combat Arms^{TM} and Arc^{TM} earplugs' level-dependent ends (Fig. 7). Although attenuation provided at incident sound pressure levels that exceed 110 dB to 120 dB for this class of HPD is much higher,[19] it is not represented in current REAT data. However, the need for these data has been anticipated with the new EPA proposed rule.[2] Because level-dependent hearing protectors are often applied for protection in rapid-onset, impulsive noise, such as that from gunfire and blasts, testing of their protective performance is much more complex than that of conventional passive HPDs.[5] Two of the most salient performance metrics regarding these designs are (1) the incident noise level that is required to elicit a sharp increase in attenuation, and (2) the response time involved in increasing the attenuation afforded to effective levels in sudden-onset noises, such as gunfire.[5,9] Extremely quick response time is of critical importance in these nonlinear, level-dependent passive HPDs. Thus, when confronted with sharply rising pressure impulses, such as those produced by gunfire, without proper measurement of the response time until a significant increase in attenuation occurs, the question remains as to whether or not the masses and frictions involved with dynamic valve systems that have moving parts overly delay the shut-off time and thus compromise protection afforded. With orifice-based systems that have no moving parts, response delays should not be of issue.

Although performance characteristics on these nonlinear attenuation metrics are not currently required by the EPA on manufacturers' packaging (nor are they typically labeled voluntarily), the EPA proposed rule does require impulsive response testing to be performed on *any* HPD sold on the basis of providing protection in impulsive noise greater than 130 dB true peak sound pressure level.[2] These impulsive tests are to be conducted using an ATF as described earlier, under the protocol of ANSI S12.42-2010.[15] Essentially, the EPA's protocol will result in a measure of the peak sound reduction provided by an HPD, with excitation impulses required in three ranges of dB true peak levels: 130–134, 148–152, and 166–170.[2] At present, the source of the impulsive stimuli are undetermined, but known techniques include long acoustic shock tubes, ammunition blanks and other explosives, and pressurized cylinders with puncturable sealing caps.[2,5] Because the noise levels at which orifice-based, passive level-dependent devices are most effective are so high (i.e., beginning at 110 dB to 120 dB),[19] tests conducted to quantify their attenuation characteristics cannot ethically or safely use human test subjects, likely even those using MIRE techniques wherein the subjects wear earplugs. The only methods currently available for this purpose involve ATFs.[2,5,15]

2.4. Passive Wave Resonance Ducted Devices

It is common practice that conventional passive HPDs primarily consist of construction materials that exhibit high sound transmission losses to create a passive barrier to airborne sound waves, and compliant materials to engage the flesh either in the ear canal, concha, or around the pinnae to form an acoustic seal. At least one configuration that augments these standard features, the SensGard ZEM^{TM} canal cap-style hearing protector, incorporates plastic "muffler tubes" or ducts that are closed at their upper ends and open at their ear canal ends to take advantage of sound wave resonance for low-frequency sounds that enter the duct. The guiding principle is that the resonance frequency of a duct closed at one end is approximated as that frequency corresponding to the wavelength that is four times the ducts length, thereby applying the "quarter-wave" resonance principle. In more precise computation, the duct's diameter is also a factor, but the quarter-wave equation is sufficient as an approximation for this discussion, and it was used in enablement of the Sensgard^{TM} HPD per its foundation patent (Zwislocki, U.S. Patent 5,824,967, 1998).[23] In the commercial embodiment of the Sensgard^{TM}, the muffler tube is about 13 cm in length, providing for quarter-wave resonance at about 650 Hz. Therefore, maximum benefit of the duct-provided noise reduction is thus limited to a low frequency that is well below the mid-to-high frequencies (i.e., above about 1000 Hz) that compose the most hazardous range to hearing, and also below those frequencies which directly overlap, and therefore mask the critical speech bandwidth (i.e., about 1000 Hz to 4000 Hz).[5,9] However, the quarter-wave resonance effect may indeed help reduce upward spread of low-frequency noise masking (at least that emanating from the 650 Hz range) into the speech bandwidth if the noise levels are sufficiently high, that is, exceeding an A-weighted noise level of about 85 dB.[9] To improve the spectral range of noise reduction of the Sensgard^{TM}, while not seen in the actual product embodiment, it would be possible to add multiple tubes to cause resonance and reduction at multiple frequencies, though this would likely make for a more bulky device, as depicted in the patent.[23] In addition to specifying the duct's length for quarter-wave resonance effect, the patent calls for the open end of the duct to impose an acoustic impedance over a wide frequency range that is *lower* than the impedance at the ear canal's opening; this is achieved by making the inner cross-sectional area of the duct larger than that of the ear canal.[23] Furthermore, the duct is said to couple with a connecting tube that provides a "tight acoustic coupling" with the ear canal to provide a seal.[23]

The acoustic input impedance and quarter-wave resonance features of this technology indeed offer a certain benefit potential. For instance, the labeled low frequency attenuation (obtained from the product package of the Sensgard ZEM^{TM} SG 26) ranges from 31.4 dB to 34.7 dB below 1000 Hz, and this is relatively high for a canal cap-type device. And the high-frequency attenuation above 1000 Hz is relatively flat, from 33.0 dB to 39.4 dB, but not enough to compare favorably with the flat attenuation HPDs discussed previously. However, it is emphasized here that with only one "muffler" duct, there will be benefit of quarter-wave resonance in only a very narrow frequency range. Also, to achieve the lower acoustic impedance of the duct as compared to the ear canal, the eartips of the device must seal in the concha of the ear instead of within the ear canal, and the concha is typically more convoluted in shape and of more widely-variable anthropometry, rendering it more difficult to seal than the ear canal. As of this writing, there was no empirical scientific research that evaluated passive ducted wave resonance devices; however, anecdotal statements of evidence appear on the Sensgard ZEM^{TM} website.[27]

Passive-ducted, wave resonance HPDs discussed under this category are simply and appropriately accommodated in the EPA proposed rule[2] using standard REAT tests, namely those of ANSI S12.6-2008.[8]

2.5. Passive Adjustable-Attenuation Devices

To help overcome the problem of overprotection in moderate noise environments, earplug augmentations have recently been developed to allow the user some level of control over the amount of attenuation achieved. These devices incorporate a leakage path that is adjustable by setting a valve that obstructs a tunnel or "vent" cut through the body of the plug, or by selecting from a choice of available filters or dampers that are inserted into the vent.

A European earplug, the Variphone^{TM},[28] is an example of an adjustable-valve design, which is constructed from an acrylic custom-molded impression of the user's ear canal. According to the manufacturer's data, the attenuation adjustment range is approximately 20 dB to 25 dB below 500 Hz, with a maximum attenuation of about 30 dB at 500 Hz. At higher frequencies, the range of adjustment decreases, while the maximum attenuation attainable increases slightly. An example of a selectable-damper design is the Sonomax SonoCustom^{TM}, manufactured in Canada.[29] The Sonomax device can be fitted with a variety of attenuation dampers that provide the opportunity for discretely variable attenuation in a single device, and each damper has distinct spectral attenuation values and NRR. Furthermore, the SonoCustom^{TM} HPD is sold as a system with a probe tube microphone test apparatus which verifies the amount of attenuation achieved via MIRE techniques on each user as they are fit with the product.

The European Variphone company, in addition to its valved earplug, manufactures other full custom-molded earplugs, including the acrylic Variphone^{TM} and silicone V-SIL^{TM} , both of which incorporate a duct into which selectable "filters" are inserted for different attenuation values. Another device which has been available for many years is the dB Blocker^{TM} from Custom Protect Ear of Canada.[30] This product is a vented, custom-molded earplug that offers different cartridge filters that can be inserted into the vent. Each cartridge comprises a unique damper/filter which affords a specific attenuation spectrum, and the selection of cartridge is based upon an analysis of the wearer's noise exposure and other needs. The cartridge is intentionally not user-replaceable, so the dB Blocker^{TM} is returned to the manufacturer should a cartridge need replacement or changing.

There are two important distinctions between these passive adjustable-attenuation HPDs and passive level-dependent HPDs that were discussed earlier. The former require user or manufacturer setting to effect attenuation changes, and the attenuation, once selected, is essentially independent of incident sound level, that is, level-independent. On the other hand, level-dependent devices react automatically to changes in incident sound pressure levels and the user has no control over the change in attenuation when the HPD is worn in its level-dependent configuration.

Attenuation testing of adjustable attenuation passive devices is only slightly more complex than for the flat-attenuation passive devices discussed earlier. For devices with discrete settings (e.g., the SonoCustom^{TM} and the dB Blocker^{TM}), the EPA proposed rule[2] specifies using the standard REAT test of ANSI S12.6-2008,[8] which is to be conducted for each level of adjustment (or for each damper/filter insert) and an NRR value is determined for each setting. Although this is time consuming and labor intensive, it is necessary protocol to quantify the performance at each setting or for each cartridge insert. Continuously variable devices (e.g., Variphone^{TM}) are more problematic to attenuation testing because they can only be tested reliably at the extremes of their adjustment range (i.e., fully open and fully closed). It is more difficult to reliably quantify the protection afforded by such devices at all intermediate settings, unless those intermediate settings are reproducible

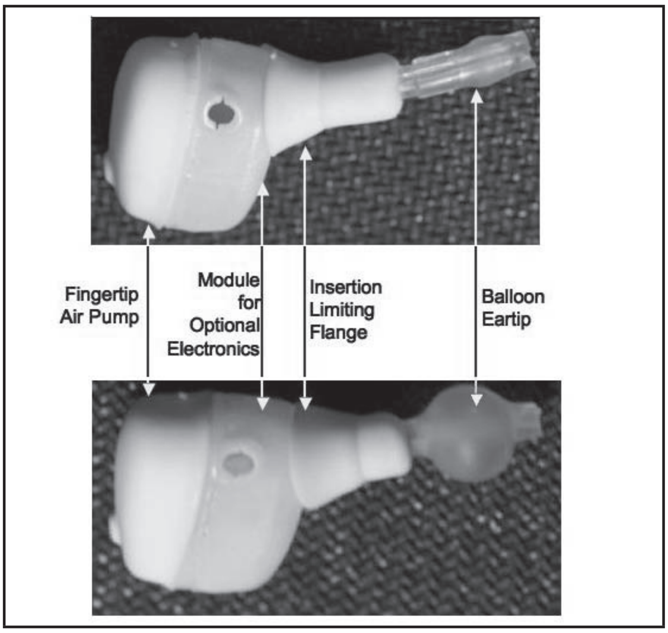

Figure 9. Prototype balloon-based ear insert with pass-through stent and pump module on end. Upper panel: Uninflated state prior to insertion. Lower panel: Inflated state after insertion. [Courtesy of J. P. Keady, Hearium Corporation, personal communication, November 14, 2009.]

through a detent or graduation setting on the valve control.

The adjustable-attenuation class of HPDs affords flexibility in product development in that these devices can be designed to allow for modular augmentations, and this is potentially a major advantage in that these relatively expensive and personalized (i.e., custom- or semi-custom-molded) earplugs can then be adapted to changing user needs and different noise environments without making a new custom-molded earplug. Filter-based devices can be tuned for specific environments or tuned to pass speech or other critical bands necessary for specific jobs, assuming that the filter's passband response is properly optimized to the objective. As this technology matures, the potential exists for additional electronic augmentations (noise cancellation, electronic filtering, closed-loop attenuation control, hearing assistive circuits, automatic gain control, digital signal recognition/processing, etc.) to also be incorporated in a modular sense, and in some cases these features have been incorporated as is discussed under the active (electronic) category shown in Table 1 of the parallel article.[1] Obviously, each of these special augmentations will require different testing/labeling procedures than afforded by the standard REAT test of ANSI S12.6-2008,[7] and not all of these technologies have been covered in the EPA's newly proposed rule.[2]

2.6. Dynamically Adjustable-Fit Devices

Many user-molded, conventional passive earplugs have been successful in the hearing protection marketplace; products are designed to provide a "one-size-fits-most" earplug that is constructed from a malleable or compressible/expandable-recovery material. Such earplugs have been made from slow-recovery polyurethane or polyvinyl foams, finely-spun fiberglass (also known as Swedish Wool^{TM}), various paraffin- and beeswax-based products, and malleable putty encapsulated inside a soft plastic sheath. While user-molded conventional earplugs could reasonably be construed to be "adjustable-fit", they all have the common denominator of being oversized in their cross-sectional diameter as compared to the ear canal into which they must be inserted. This "oversize design" emanates from the need to compress the earplug (or otherwise force it to conform to the ear canal) to develop an acoustic seal against the canal walls. Of course, in order to achieve a quality fit, the user must first manually "mold" or form (via finger-exerted compression and/or elongation force) the earplug into an "undersize" shape before it is actually inserted, and then to quickly insert it before it returns to its original shape and size, which occurs with foam and some other elastic materials. For some users, this manipulation of the earplug prior to insertion and subsequent prompt insertion can be difficult.[6,9] Furthermore, foam, putty, or wax-based earplugs cannot be "dynamically" adjusted inside the canal once they have been inserted; instead, they must be fully removed from the ear canal, and then a new molding/insertion process must commence.

A very recent development that overcomes this common "oversize" disadvantage to user-molded earplugs is dynamically-adjustable ear inserts that are based loosely on angioplasty balloon technology. These designs are taught in several published patent applications (e.g., Goldstein and Keady, U.S. Patent Appl. 20090022353;[24] Keady, U.S. Patent Appl. 20090245530[25]). As shown in Fig. 9, these devices are distinguished by the fact that the balloon and its longitudinal support structure are well under the size of the cross-sectional area of the ear canal and thus can be inserted without user manipulation. Once inserted into place, and resting at a depth limited by a "stop flange" on the outside of the balloon, the user manually inflates the balloon to fit his/her ear canal at a comfortable pressure via a few presses of the integrated manual pump that is located outside of the ear canal but in the concha region. At the time of this writing, these adjustable-size inserts had been prototyped in a configuration which comprises a stent or tube though the center of the balloon to provide a sound pathway duct, and at its distal end, a tiny fingertip pump to inflate the balloon once it is in the ear canal (Fig. 9). The adjustment of the balloon pressure is considered dynamic because the user can, at any time, deflate or readjust pressure after the balloon is inserted into the ear. The pump is integrated with a module that can house electronics, batteries, microphones, or other features. The pass-through sound port can be eliminated or plugged to achieve a purely passive HPD, or it can remain open for venting or transmission of signals or speech from a tiny loudspeaker in the device's outer module.

The author has been involved with developmental evaluations on the balloon-based ear insert, and beyond the aforementioned patent applications, no published data on attenuation or other performance aspects are available at the time of this writing. Given that this balloon technology has just recently been prototyped, more research on its performance capabilities is recommended before it is used as a basis for hearing protection.

As for attenuation testing protocol for the adjustable-fit balloon inserts, due to the fact that their insertion loss is provided strictly via passive means, the appropriate test under the EPA proposed rule[2] is the standard REAT test of ANSI S12.6-2008.[8]

3. SUMMARY

Based on this review, there have been significant advancements in passive augmentations to hearing protectors in the past two decades. Some of these devices pose attenuation and other performance testing challenges, but in all cases noted above, the EPA's newly proposed rule[2] offers a viable approach to accomplishing the testing. Passive augmentations have indeed been innovative, as evidenced by the number of patents awarded for their designs and methods. The reader is now referred to the parallel publication by Casali[1] for a review of active (electronic) augmentations.

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