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AMERICAN INDUSTRIAL HYGIENE ASSOCIATION JOURNAL 57:175–185 (1996)

Technology Advancements in Hearing Protection Circa 1995: Active Noise Reduction, Frequency/Amplitude-Sensitivity, and Uniform Attenuation

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Conventional hearing protection devices represent a mature technology that has been widely used since the late 1950s. When worn consistently and correctly such devices can provide suitable hearing protection in many, if not most noise-hazardous or aurally annoying situations. However, such devices have often been implicated in compromised auditory perception, degraded signal detection, and reduced speech communication abilities. In some instances this can create hazards for the wearer, or at the very least, resistance to use by those in need of hearing protection. Recent technological developments have been used to augment hearing protectors in an attempt to alleviate these problems for the user while providing adequate attenuation. Operational characteristics, design alternatives, performance data, and applications for active noise reduction, active sound transmission, frequency selectivity, adjustable attenuation, amplitude sensitivity, and uniform attenuation features in hearing protectors are discussed, and recommendations are provided.

Keyword: hearing protection

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To combat the threat of noise-induced hearing loss posed by intense noise environments, hearing protection devices (HPDs) have been an item of personal safety gear since the 1950s. At about the same time, organized hearing conservation programs first appeared in the U.S. military. With the promulgation in 1971 of the Occupational Safety and Health Administration (OSHA) Noise Standard[1] and in 1983 of the OSHA Hearing Conservation Amendment,[2] the use of hearing protectors has proliferated in U.S. industrial workplaces. Recently there has been some indication that HPDs are becoming more popular among the general public, especially with those individuals who regularly engage in loud recreational activities such as target shooting, power tool operation, and noisy spectator events such as vehicle racing.

Basic styles of HPDs in common use include earplugs that are inserted into the ear canal, ear canal caps that seal the canal at or near its rim, and earmuffs that encircle the outer ear. So-called "conventional" HPDs constitute the vast majority of such devices. These basic HPDs produce attenuation of noise strictly by passive means without the use of electronic circuitry, and result in a noise reduction between the environmental sound level and the sound level under the protector. Passive attenuation is accomplished via one or more avenues, including the use of construction materials with high sound transmission loss properties, liner materials that absorb and dissipate sound, trapped air volumes that provide acoustical impedance, and compliant materials that establish an acoustical seal against the skin.

When properly selected for the situation and correctly worn by the user, conventional passive HPDs can provide adequate protection in most industrial, military, and recreational environments. However, due to the very nature of the attenuation they provide, concomitant effects on hearing quality and auditory performance often accompany the noise reduction afforded.

Conventional HPDs: Effects on Auditory Perception

A distillation of the research evidence from normal hearers generally suggests that conventional passive HPDs have little or no degrading effect on the wearer's understanding of speech sounds in the sound field outside the HPD in ambient noise levels above about 80 dBA, but that they do cause increased misunderstanding over unoccluded conditions in lower sound levels. Although HPDs are not required below 80 dBA, they may be desired for reduction of annoyance or worn for convenience, so that when at some later time an intermittent sound increases in magnitude, the wearer will already have the HPD in place. In the latter case the use of conventional protectors in the quiet periods of intermittent noise can be problematic.

At ambient noise levels greater than about 85 dBA, most studies have reported slight improvements in intelligibility with certain HPDs,[3,4] while others attempting to simulate on-the-job conditions have reported small decrements, especially when the speaker is also wearing protection that causes a reduction of voice output.[5] Noise- and age-induced hearing losses generally occur in the high-frequency regions first, and for those so impaired, the effects of HPDs on speech perception are not clear-cut. These persons are certainly at a disadvantage, because their already elevated thresholds for mid- to high-frequency speech sounds are further raised by the protector. Though there is no consensus among studies, it appears that sufficiently hearing-impaired individuals will usually experience reduced communications abilities with HPDs worn in noise.[6]

Because conventional HPDs do not differentiate and selectively pass speech (or nonverbal signal) versus noise energy at a given frequency, the devices do not improve the speech/noise ratio, which is the most important factor for achieving reliable intelligibility. In fact, nearly all conventional devices attenuate high-frequency sound more than low-frequency sound, thereby reducing the power of consonant sounds that are important for phoneme discrimination and also allowing low-frequency noise through, thus creating an associated upward spread of masking. While increased attenuation as a function of increasing frequency comprises the general spectral profile of conventional HPDs, it should be noted that inter- and intra-HPD category differences do exist. For instance, earmuffs as a category generally exhibit a slight attenuation advantage in the midfrequencies over earplugs, while the reverse is true at low frequencies.

How then do protectors sometimes afford intelligibility improvements in certain high-noise situations? The accepted theoretical explanation is that by lowering the total incident energy of both speech and noise, HPDs alleviate cochlear distortion that occurs at high sound levels. Acoustic glare is thereby reduced and the sensorineural system operates under more favorable conditions in which better discrimination can occur. The situation is analogous to the reduction in visual glare and enhanced vision that results from the use of sunglasses on a bright day. However, it must be kept in mind that prediction of the effects of protectors on speech intelligibility in noise is a complex issue that depends on a host of factors, including the listener's hearing abilities, whether or not the speaker is occluded and/or in noise, HPD attenuation, speech and noise levels, reverberation time of the environment, facial expressions and lip movements, and content/complexity of the message to be interpreted. Differences in testing protocol with respect to these factors contribute to the variance in reported results across studies.

The same HPD influence on signal/noise ratio and the theoretical basis for reducing cochlear distortion apply to the detection and recognition of nonverbal signals, such as warning horns or sirens, annunciators, and machinery sounds. The high-frequency bias in attenuation of conventional HPDs, coupled with the typically elevated high-frequency thresholds of those with noise-induced hearing loss and the upward spread of masking from low-frequency noise, render warning signals and sounds above about 2000 Hz the ones most likely to be missed. However, warning signal parameters such as frequency, intensity, and temporal profile may be designed to help alleviate detection problems.

Also due to the increased attenuation with frequency, conventional HPDs create an imbalance in the listener's experience of the relative amplitudes of different pitches and cause broadband acoustic signals to be heard as spectrally different from normal, in that they take on a muffled, sometimes bass tone. However, while signal interpretation may be affected, the bulk of empirical studies with noise levels ranging from 75 to 120 dB indicate that signal detection will not be compromised by HPDs for normal-hearing individuals.[7] While the evidence is less extensive for hearing-impaired listeners, they can be expected to experience detection and recognition difficulty, depending on their hearing loss, the particular signal, ambient noise, and hearing protector worn.

Since some of the high-frequency binaural cues (especially above about 4000 Hz) that depend on the pinnae are altered by HPDs, judgments of sound direction and distance may be compromised. Earmuffs, which completely obscure the pinnae, radically interfere with localization in the vertical plane and also tend to cause horizontal plane errors in both contralateral (left-right) and ipsilateral (front-back) judgments.[6] Earplugs may result in some ipsilateral judgment errors but generally cause fewer localization problems than muffs. Exceptions exist, however, in that at least one high-attenuation earplug has been observed to disrupt localization in similar magnitude to muffs.[8] There are also theoretically based suggestions that HPDs may interfere with the ability to judge distance to a sound source,[7] but the only published empirical study of which the authors are aware reported no measurable effect for the one earplug that was tested.[9]

The Need for Special HPDs

As a result of the undesirable auditory effects of conventional HPDs as previously described, especially for people with existing hearing impairments, special consideration is required when specifying signal/noise ratios and other design parameters for communications and auditory warning systems. As an alternative, or in addition to adjusting the communications system parameters, the HPD itself offers an opportunity for change. Of course, it is absolutely essential that an individual's auditory sensitivity be preserved via the proper use of an adequate protector, but if the device can provide both acceptable attenuation and augmented auditory perception, it will more likely be worn, improving the hearing conservation effort, and will offer additional safety benefits as well. For this reason, new HPD designs have been developed to improve communication and signal reception for the wearer exposed to noise. Of these, technologies which incorporate electronics to achieve such features as noise cancellation, signal transmission, or DC-powered communications capabilities are typically termed "active," while those that rely strictly on mechanical means to provide various qualities such as amplitude-sensitive or uniform attenuation are termed "passive."

Active HPDs

Active HPDs may be broadly defined as earplugs, canal caps, earmuffs, or noise-attenuating helmets that incorporate electronic components and transducers. They may be designed to amplify sounds detected by a microphone in an ambient sound field, or transmitted via wired or wireless communications. The amplification may vary with sound level or be level-independent. Communications capabilities may or may not be included. Bolstered by continuing advances in microelectronics and computer technology, the active approaches described next currently represent perhaps the most fertile ground for hearing protection development.

Active Noise Reduction HPDs

Active noise reduction (ANR) relies on the principle of destructive interference of equal amplitude but exactly out-of-phase sound waves at a given point in space; in the case of hearing protectors, the cancellation is established at the ear. Although the first ANR headset appeared as a working model in 1957,[10] only in the past decade have major advances in miniature semiconductor technology and high-speed signal processing enabled ANR-based HPDs and communications headsets to become viable products.

ANR has been incorporated into two types of personal systems: (1) those designed solely for hearing protection, and (2) those designed for one- or two-way communication having the associated required boom- or throat-mounted microphone and earphone components (commonly referred to as ANR headsets and discussed later in this article and elsewhere).[11] Both types are further dichotomized into open-back (or supra-aural) and closed-back (or circumaural earmuff) variations. In the former a lightweight headband connects ANR microphone/earphone assemblies surrounded by foam pads that rest on the pinnae. In that there are no earmuff cups to afford passive protection, the open-back devices provide only active noise reduction, and if there is electronic failure, no protection is provided by the device. Closed-back devices, which represent most ANR-based HPDs to date, are typically based on a passive noise-attenuating earmuff that houses the ANR transducers, and in some cases, the ANR signal processing electronics. The ANR electronics and/or power supply may also be located on a belt-mounted pack and connected via cable to the headset. If backup attenuation must be provided by the device in the event of electronic failure of the ANR circuit, the closed-back HPD is advantageous due to the passive attenuation established by its earcup.

Analog ANR Devices

A generic block diagram depicting the typical components of an analog electronics, feedback-type, muff-based ANR HPD appears in Figure 1. The example is a closed-loop feedback system that receives input from a sensing microphone that detects the noise that has penetrated the passive barrier posed by the earmuff. The signal is then fed back through a phase compensation filter that reverses the phase, to an amplifier that provides the necessary gain, and finally is output as an antinoise signal through an earphone loudspeaker to effect cancellation inside the earcup. Although most ANR devices have been built in earmuff or supra-aural headset configurations, an earplug example has also recently been prototyped.[12] In contrast to the common ANR closed-loop feedback configuration shown in Figure 1, open-loop feed-forward systems are also available; these are typically of the lightweight headset (i.e., open-back) variety.

Nearly all data published in the open literature on ANR-based hearing protectors concern analog, earmuff-type devices; recent example data may be found in Nixon et al.[13] and Rylands.[14] To achieve maximal noise cancellation, physical mixing of the antinoise field with the offending noise field is critical, so correct geometric placement of transducer components, as well as accurate timing in the presentation of the antinoise, are fundamental to the success of an ANR device. In an ideal sense, because ANR circuitry adds two out-of-phase noises that are of equal amplitude, the resultant amplitude should be zero and the effect one of complete cancellation. But this would require propagation with zero time delay between the various system transducers and the eardrum, which is physically impossible with the earphone, microphone, and listener's eardrum all located at different points in space. Due to the phase shifts that can be attributed to these transducer location differences, as well as the possibility of throughput delays in signal processing, establishing the correct phase relationship of cancellation signal and noise becomes more difficult as the bandwidth of the noise increases; therefore, ANR has typically been most effective against low-frequency noise. For example, with contemporary analog ANR devices, maximal attenuation values of about 22 dB are typically found to be in a range from about 100 to 250 Hz, dropping to essentially no attenuation above about 1000 Hz.[13] Noise enhancement (typically 3 to 6 dB, but in some cases more) occurs in the midrange frequencies (about 1000 to 3000 Hz) with some analog ANR devices.[13] This can occur when the overall acoustic gain is close to unity and the phase relationship is close to the in-phase condition, producing addition rather than cancellation. In the midrange, due to transducer and headset characteristics, there may be a rapid variation in phase with frequency that can result in wave addition. Midrange enhancement in some devices has manifested when a loss of earmuff cushion seal occurs, resulting in instabilities in the cancellation system.[13] However, it has been demonstrated that enhancement can be minimized with correct electroacoustic design.[15]

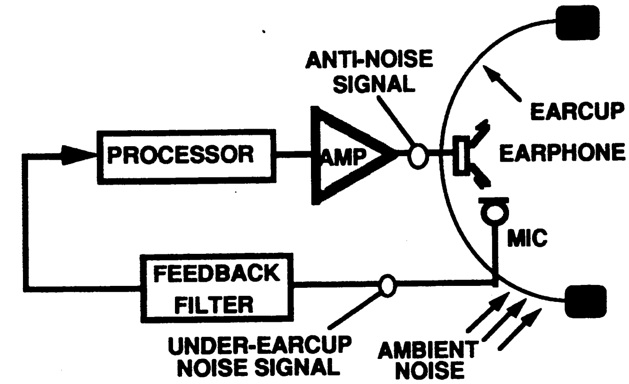

FIGURE 1. Block diagram depicting typical components of an analog ANR-based HPD of the closed-back variety

An example of the performance of an ANR headset in terms of its inherent passive attenuation compared with its total attenuation (i.e., the ANR-on mode) is provided in Figure 2.[16] The computed active attenuation—that is, the difference between the total attenuation and the passive attenuation—is also shown to highlight the range in which the ANR circuitry functions most effectively. The high gains in low-frequency attenuation and losses in the midrange frequencies referred to above are clearly illustrated. As depicted in Figure 3, when example attenuation data for a closed-back ANR headset are used in computation of a daily noise dose for noise at 115 dB(linear), the benefit of the active attenuation circuit over that of the ANR unit in its passive mode in reducing exposure levels is quite dramatic, especially for a low-frequency biased tank noise.[11]

The low-frequency effectiveness demonstrated in analog ANR tests to date is particularly fortuitous for earmuff design in that

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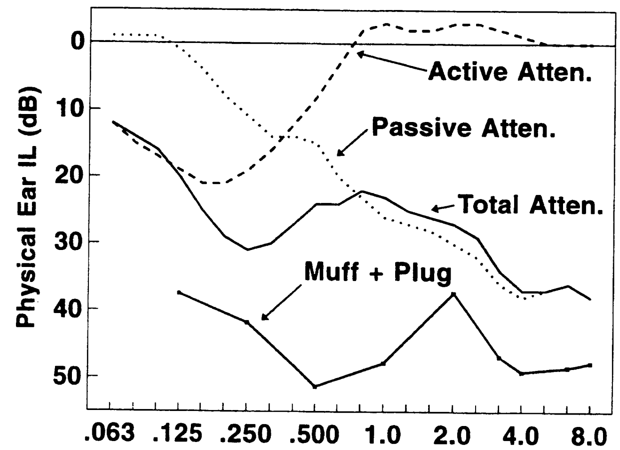

FIGURE 2. Microphone-in-real-ear insertion loss (IL) values for a high-performance closed-back ANR headset in the passive-only, active-only, and total (ANR on, i.e., active + passive) modes.[16] For comparison, the real-ear attenuation of a dual hearing protector (i.e., well-fitted foam earplug plus earmuff) are shown (adapted from Berger).[17]

ANR can potentially bolster the low-frequency attenuation of conventional passive earmuffs, which tend to be most protective in the frequencies above 1000 Hz. However, there are sizable incremental cost and weight tradeoffs associated with the addition of ANR components to a passive muff; therefore, it is important that the gain in low-frequency attenuation be significant over that afforded by the muff alone. Furthermore, the ANR earphone/microphone components partially fill the occluded volume under a passive earmuff; the concomitant reduction in the acoustical impedance afforded by the trapped air mass decreases the passive attenuation afforded, especially at the low and middle frequencies.

Digital ANR Devices

With advances in the speed, power, reliability, and miniaturization of digital signal processing components, digital technology has demonstrated promise for improving the capabilities of ANR-based HPDs, particularly in regard to precise tuning of the control system via software for optimizing the cancellation of specific sound frequencies. Advantages of the use of digital technology as generally compared with analog reside largely in its ability to perform complex computations with high precision, in that electronic components are less affected by temperature variations and remain more stable, and in the fact that performance tolerances can be held very tight. Some ANR HPDs incorporate hybrid analog/digital designs.

The digital approach offers considerable flexibility in establishing the ANR, and several different techniques have been developed and implemented. It is beyond the scope of this article to cover all of the digital techniques used to date, and performance data on digital devices are lacking in the open literature; therefore, only one example of a contemporary digital system, with attenuation data, will be discussed. A brief overview of other digital techniques appears in Casali and Robinson.[18] The digital approach used as an example relies on feedback control and a residual (under earcup) microphone for sensing the sound at the ear. It is particularly beneficial when the noise is tonal/narrow-band in nature, such as an emergency vehicle siren, for which precise tuning is needed.[19] This approach has been used successfully in open-back HPDs to cancel periodic noise, wherein the repetitions are identical or near-identical so the noise is highly predictable, as in the case of vehicle sirens.[19]

A block diagram of the major components of a digital ANR system, showing one earphone, appears in Figure 4. A residual microphone transduces the noise at the ear providing the input to the digital controller, allowing it to create an antinoise signal continuously that is presented via the headset speaker to minimize the noise at that ear. The internal operation of the controller can be best described starting at the output of the adaptive filter. The adaptive filter generates the antinoise signal, which is passed through an equalizing filter (designed to match the acoustics of the headset), creating a signal that approximates the acoustical antinoise as would be heard by the residual microphone. Subtracting this signal from the residual noise signal then recreates an approximation of the original noise that would be heard at the ear if the ANR were turned off. The regenerated reference signal is the input to a classical least mean square adaptive filter, which compares the regenerated reference signal to the residual signal to determine updates to its internal parameters continuously to minimize the energy in the residual signal.[19]

Siren signals are typically frequency-modulated over a cycle, and due to acoustical and resonance effects in the vehicle cab, produce rapidly varying amplitudes during each cycle as the frequency

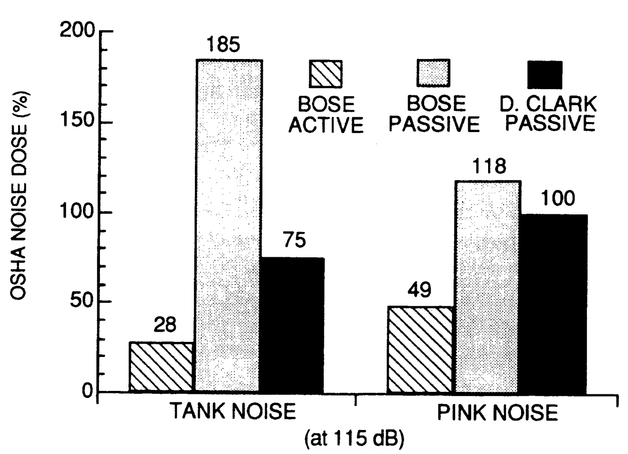

FIGURE 3. OSHA daily noise doses under an ANR closed-back headset in passive-only and active (passive + active attenuation) modes and for a conventional passive headset computed from attenuation spectra and 115 dB noise (adapted from Casali and Gower)[11]

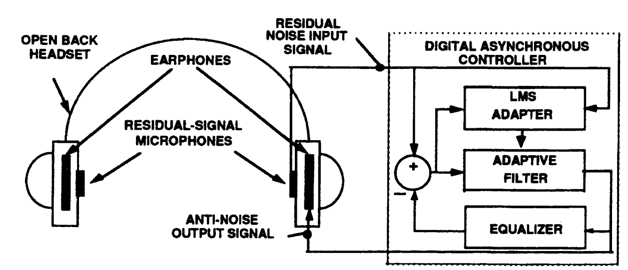

FIGURE 4. Block diagram depicting typical components of a digital ANR-based hearing protector of the open-back, asynchronous feedback variety (adapted from Denenberg and Claybaugh with modifications)[19]

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slews. Effective cancellation of such a signal necessitates a system that adapts to the sound variations at a rate faster than those variations actually occur in the sound field. Recent attenuation tests with a digital HPD designed to combat emergency vehicle siren noise indicated that at the peak frequencies for a particular test siren, active attenuation was significant, ranging from approximately 8 to 20 dB at 800 Hz, and up to about 15 dB at 4000 Hz. (These results were obtained under controlled laboratory conditions with only the siren noise present and may change under field conditions with concurrent ambient noise sources, such as the emergency vehicle's engine noise.) Some earphone distortion and reduction in attenuation occurred at the highest L_{eq} siren level of 100 dB(linear), and siren modes with very high frequency slew rates (180 cycles/min) were associated with the lowest attenuation.[18] Example attenuation data from tests using microphones in real (human) ears (MIRE) and manikin tests are plotted in Figure 5 for one siren. It appears that digital ANR technology offers promise for providing selective-frequency protection in certain tonal noise hazards, with the concomitant potential benefits to communications and user comfort of a lightweight supra-aural headphone.

Applications for ANR-Based HPDs

The synergistic benefits of both active and passive attenuation in a well-designed ANR closed-back HPD should prove quite useful in certain noise environments. The major benefit of most current analog devices will be apparent in noisy areas with a strong bias toward low-frequency sound spectra. If one can be assured that the spectrum is exclusively low frequency, open-back (supra-aural) ANR devices may suffice, but it must be stressed to users that no protection is afforded if the ANR circuitry fails. Open-back devices are a particularly attractive alternative in hot environments and when acoustical signals and/or voice must be heard from outside the headset.

A relatively untapped area of application for ANR headsets is that of narrow-band, or near-tonal, machinery noise in industry. With most rotating or reciprocating machinery, the noise emission often consists primarily of energy at the fundamental and harmonics of a firing frequency or rotation rate; for these types of sources, the noise is approximately periodic, often accompanied by a contribution of broadband random energy at lower amplitudes. If the broadband noise reduction requirements for these applications are not significant, the ANR-based HPDs can be designed as open-back, with the accompanying advantages. Examples of equipment with heavy concentrations of narrow-band noise output include emergency vehicle sirens, internal combustion engines, air compressors, air bleed valves, friction brakes, certain vacuums, large power transformers, pumps, and some fans.

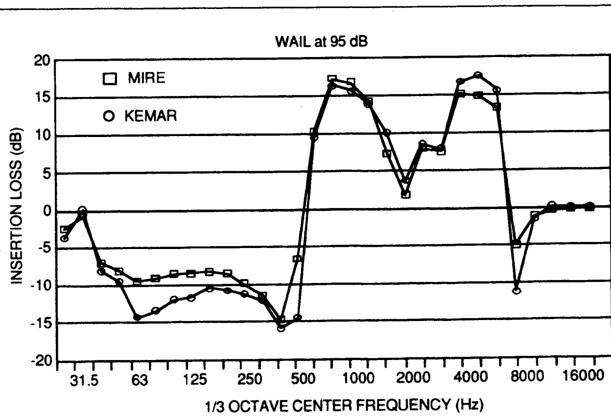

FIGURE 5. Attenuation of siren-canceling headset (Noise Cancellation Technologies) as obtained with MIRE and KEMAR (manikin) insertion loss measurements using a Federal Signal Wail siren at 95 dB Leq. (adapted from Casali and Robinson)[18]

Reliability/Maintainability and Other Issues with ANR-Based HPDs

Especially in harsh environments, reliability should be a consideration in the selection of ANR devices. Complete failure of an earmuff-based ANR device is not disastrous, of course, because the passive attenuation of the muff itself is unaffected, and the wearer is afforded some protection until the device can be repaired. However, partial malfunction of the electronics may be worse than total failure, because if there are problems in processing and presenting the cancellation signal, noise exposure can be amplified. Another consideration with the use of battery-powered ANR headsets is that maintenance must receive special attention, especially with the need for periodic battery recharging and replacement. This is not an issue in vehicle cabs where the units may be powered with the vehicle's available DC supply, such as through an intercom connection, but it is disadvantageous on the industrial shop floor or outdoors.

Another shortcoming in certain ANR designs is lack of sufficient amplifier gain and/or output from the sound-canceling earphone to effect sufficient active noise reduction as sound levels approach and exceed 120 dB.[13] Although such levels are not common in industry, they are experienced in military operations, and it is at just such excessive levels that the user is most in need of the extra attenuation that can be provided by ANR.

A potential advantage of ANR systems is shown by subjects having anecdotally indicated that they feel more "comfortable" with the noise reduction that ANR provides, particularly that associated with quieting loud low-frequency rumble or intense intrusive noises such as sirens. With open-back ANR devices, comfort advantages over passive earmuffs may be realized due to lower weight and headband force, but the complete lack of passive attenuation must be considered carefully when opting for an open-back device. Compared with conventional passive or even amplitude-sensitive protectors, ANR-based HPDs command a relatively high price of \$150 to \$1000 per unit. Thus the initial cost is much higher than that of conventional passive HPDs, and maintenance costs, including battery replacement, are expected to be higher as well. However, the high initial costs of an ANR device may be somewhat offset if the attenuation advantage is sufficient to yield improved protection, reduced noise-exposure doses, and longer allowable working periods, and ultimately, reduced compensable hearing loss claims. At the present state of the technology, the potential for such an ANR advantage is small and specific to certain noise environments, especially those of low-frequency energy bias and some of tonal noise characteristics. Another issue that presently inhibits the use of ANR devices is that testing protocols for establishing and forming a basis for labeling the attenuation of ANR-based HPDs are not yet standardized nor adopted into federal codes. Due to the nature of these electronic devices, the testing requirements pose some formidable protocol and instrumentation issues.

In considering an ANR-based HPD as an alternative to conventional passive devices, it is valuable to gain the perspective of the data in Figure 2, which compares the attenuation achievable from a combination of a conventional passive earplug and earmuff worn together versus an example of ANR-based earmuff performance. The initial cost of the dual passive HPDs is less than about \$20, as compared with hundreds of dollars for the active system.

The attenuation of the optimally fitted dual protector exceeds that of the properly functioning ANR device. What distinguishes them will be the human-factors aspects of fitting, using, and maintaining the devices, and the specific application to which they will be directed. One consideration is that the dual protection requires more attention to fitting and storage due to the presence of two separate devices. On the other hand, the ANR device requires more maintenance and care in handling.

A final remark concerning ANR earmuffs pertains to subjective demonstrations of their effectiveness. As alluded to earlier, the passive attenuation of an ANR earmuff is generally degraded in the 100–1000 Hz frequency range because it is filled with electroacoustic components. This makes it somewhat misleading to evaluate, on a subjective basis, the performance of the ANR feature by simply switching on and off the ANR electronics. Even though a large difference in low-frequency sound transmission may be heard when comparing the on and off conditions of an ANR system, this effect is misleading. The incremental benefit of an ANR system that is actually of value to the wearer is the noise reduction of the ANR system in the on mode, versus that of the same earmuff cups without the ANR components installed. That effect will always be less than the on/off difference. Unfortunately, a direct comparison of the ANR-on and the cup-empty conditions is normally difficult or impossible in practice.

Amplitude-Sensitive Sound Transmission HPDs

These electronically augmented HPDs consist of modified conventional earmuffs or earplugs that house microphone and output-limited amplifier systems to transmit external sounds to earphones mounted within the earcups. The electronics can be designed to pass and boost only those sounds within a desired passband, such as the critical speech band. Typically, the limiting amplifier maintains a predetermined (in some cases user-adjustable) earphone level, often at about 82–85 dBA, unless the ambient noise reaches a cutoff level of 115 to 120 dBA, at which point the electronics cease function.[20]

Ideal and typical performance for active sound transmission systems are illustrated in Figure 6.[20] The gain for the system at low sound levels may be set anywhere from a negative value (which in essence provides a degree of noise reduction) to a positive value; an example of 6 dB positive gain is shown in the figure. The maximum attenuation the active sound-transmission device can provide occurs at levels at and beyond which the electronic circuitry has cut off. Then the earmuff continues to provide the passive attenuation of its earcups as shown by the right-most diagonal line (labeled "off") in Figure 6. Presuming that the microphone and cable penetrations through the cup are properly designed and acoustically sealed, the performance of the system with the electronics cut off should be approximately the same as the equivalent passive earmuff without the electronics and transducers mounted therein.

A limitation in current sound transmission devices concerns distortion products, as illustrated in Figure 7 for two commercially available amplitude-sensitive active sound transmission circumaural HPDs.[21] Both devices transmit a significantly distorted signal to the ear when the input is a high-level steady-state band of noise that pushes the electronics into the limiting/clipping mode. This condition is representative of how some devices perform in typical high-level occupational noises. The subjective impression is of a raspy, crackling sound sometimes accompanied by static or popping noises. Not only may this produce annoyance, but it also degrades the understandability of speech coming through the earphone.

Dynamic noise attenuation and user hearing acuity under sound transmission earmuffs depend on a host of electronic system design factors such as cutoff sound level and sharpness of attenuation transition at this level, response time to impulses, frequency response and bandwidth, distortion and residual electronic noise, signal/noise ratio at sound levels below the cutoff, sensitivity to wind noise, and battery life/rechargeability. There is considerable variance among available products with respect to these factors.

Another design issue is that of microphone configuration. It may be diotic, wherein a single microphone in one earcup feeds both earphones, or binaural (technically called dichotic, commonly called stereo), in which each earcup has an independent microphone to simulate the situation that is present with the actual unprotected pair of ears. The latter approach provides better localization performance for situations in which wearers must ascertain the source and direction of environmental sounds.[22]

Electronic earmuffs can improve the ability of hearing-impaired listeners to detect sounds in quiet surroundings in much the same manner as can a hearing aid. However, the frequency response of the system will substantially affect sound quality. Despite the claims of some manufacturers, such improvements typically cannot be

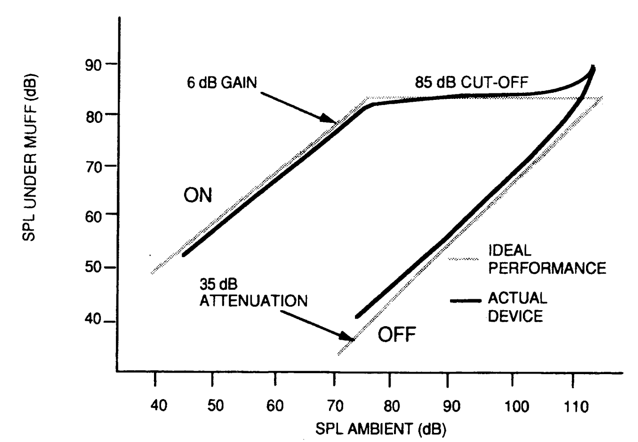

FIGURE 6. Ideal and representative performance for an active sound transmission earmuff (adapted from Maxwell et al.)[20]

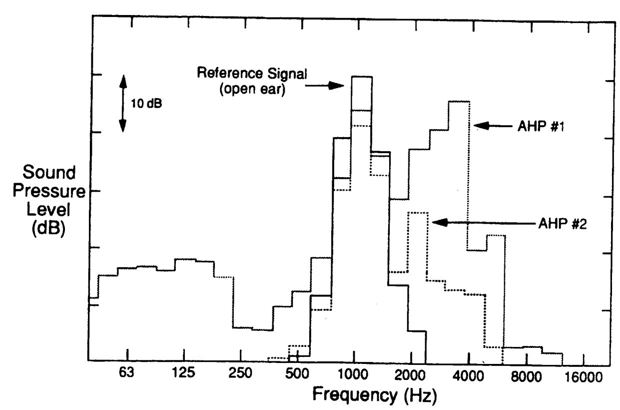

FIGURE 7. Illustration of distortion in active sound transmission hearing protectors (AHP) as measured on an acoustical manikin (KEMAR) for an input signal consisting of a 93-dBL, 1-kHz, 1/3-octave band of noise presented in a diffuse sound field. The reference signal is measured at KEMAR's eardrum with no protector in position (adapted from Berger).[21]

realized for normal-hearing listeners. Although the amplified sounds may be louder than heard by the unaided ear, the residual electronic noise that is present in some active devices will also be amplified and audible, and will mask the threshold-level signals the listener is trying to detect.[23]

In comparison with both conventional and passive amplitude-sensitive earmuffs, active sound transmission earmuffs are more expensive (upwards of $100) but offer a viable alternative for use in intermittent noises, especially those with impulse-type (e.g., gunfire) or short-duration on-segments. Thus, active sound transmission HPDs are well-suited to shooting applications as a more expensive alternative to the passive amplitude-sensitive designs. They provide for potentially excellent communications when the impulses are not present and yet, if properly designed, can offer adequate protection against the peak levels of the gunshots.

In intermittent noise with short on-durations (occasional high-level sounds separated by long quiet intervals), active sound transmission devices are also useful. However, due to the distortion discussed above, current designs are not well-suited to noises with long on-durations at high levels, since during those periods their limiter circuits will be operational and distorted, potentially impairing discrimination and causing listener fatigue and annoyance. For applications of the latter variety, a flat attenuation, moderate attenuation, or conventional HPD would be preferred depending on the type and level of noise present.

HPDs with Communications Features

For provision of communication or music signals at the ear, small loudspeakers have been integrated into HPDs. Headsets (including ANR examples) consist of earphones housed in earmuff earcups that can support a directional microphone (often noise-canceling and/or voice-activated) in front of the mouth. Small receivers can also be remotely located on a hard-hat or behind the pinna and coupled to the ear via tubing through earplugs. An alternative is an earplug-like unit, called an ear microphone, which consists of a receiver button and a microphone that picks up the wearer's voice as a result of sound radiation from the bone-conduction-excited ear canal walls, or through air conduction of the voice from the mouth to the microphone mounted on the outside of the earplug. Each of these approaches is available as one- or two-way systems using wireless (radio frequency or infrared) or wired technology.

It is important that communications earphones and receiver buttons be output-limited so that amplified signal levels do not pose a hearing hazard. Also, in the case of an ear microphone, adequate isolation of microphone and earphone is essential to avoid feedback squeal problems at the ear and picking up ambient air-conducted noise in the microphone. Furthermore, care must be exercised when selecting such a communications device that must double as a hearing protector. While some circumaural devices provide passive attenuation comparable to a standard earmuff, ear microphones typically provide less protection than comparable conventional earplugs.[24]

In cases where the attenuation afforded by a circumaural headset is inadequate such that communications signals are noise-masked, improvements can be realized by wearing an earplug under the headset. While the earplug will reduce the communications signal as well as the noise, the signal/noise ratio in the ear canal can be improved if the earphone provides sufficient distortion-free gain to compensate for the insertion loss of the earplug. Other enhancements may be provided in the system electronics, such as peak-clipping and signal conditioning, to enhance the acoustic power of consonants that are critical to word discrimination.

Communications headsets have also been augmented with ANR technology. To convert the analog ANR HPD block diagram of Figure 1 to a communications headset, a pre-emphasized speech intercom signal can be added as an input to a comparator, which would have as a second input the noise feedback leg. The intercom signal typically requires pre-emphasis to offset the effect of the cancellation circuit on the amplitude of the low frequencies in the speech. After comparing the desired speech input with the noise feedback, the comparator's output (difference) signal is then processed through an earphone compensation/amplifier circuit, resulting in a speech signal being added to the antinoise signal that is broadcast from the earphone. Intercom signals are intended to be reproduced in the earphone relatively unchanged; however, airborne voice and sounds that penetrate the earcup are partially canceled by the ANR in the low frequencies and attenuated in the high frequencies by the passive attenuation of the earmuff. Thus, the primary intent of this type of closed-back ANR headset is to enhance the intelligibility of the intercom channel.

Studies to date concerning analog ANR headset intelligibility show mixed results. With the ANR headsets operated in their active mode versus their passive (ANR off) mode, there are instances where certain ANR devices provide intelligibility benefits on the order of 10–20% over ANR-off conditions, while other devices exhibit no benefit when the ANR is on.[13] When a particular commercial aviation ANR headset was compared against a quality conventional passive headset, one study showed no advantage of the ANR device as measured by either speech/noise ratio or intelligibility scores (in the mid-80% range for 115 dB noise).[11]

Passive HPDs

Augmented HPDs of the passive category are those containing structural elements and mechanical devices such as apertures, ducts, diaphragms, dampers, valves, and springs, but no electronic components or transducers. As such, passive devices are less expensive than their active counterparts, generally are more durable and require less maintenance (and of course no battery replacement), and more closely resemble conventional HPDs. With creative designs they can provide valuable performance gains, but are more limited in the features they provide than are the active devices.

Frequency-Sensitive HPDs

Relatively inexpensive and technically straightforward efforts to improve communication under earplugs have involved the use of apertures or channels through an earplug body. One early technique incorporated an air-filled cavity encapsulated by the walls of a premolded earplug.[25] In such a design the cavity is vented to the outside and also to the ear canal via a tiny port on each end. This creates a two-section low-pass filter that can be designed to provide attenuation that dramatically increases with frequency, yielding negligible attenuation below about 1000 Hz but up to about 35 dB at 8000 Hz. Because most of the speech frequencies critical to intelligibility lie in the 1000 to 4000 Hz range, the communications benefit potential of the low-pass feature may be relatively small depending on the situation, especially in noisy environments that have considerable low-frequency energy that causes a spread of masking upward into the critical speech band.

A simpler approach, common today in custom-molded earplugs, is to drill a small (about 0.5 mm) channel or stepped-size vent longitudinally through the plug. The resultant air leak typically reduces attenuation in the low frequencies to a greater extent than in the high, roughly providing a low-pass characteristic. Depending on the size of the port and any acoustical damping material placed therein, the attenuation achieved may be insufficient for many industrial noise environments. Real-ear attenuation data for representative earplugs of the passive, frequency-sensitive variety are shown in Figure 8.[21]

Adjustable-Attenuation HPDs

To help overcome the problem of overprotection in moderate noise environments, earplug designs have recently been developed that allow the user some level of control over the amount of attenuation achieved. These devices incorporate a leakage path that is user-adjustable via the setting of a valve that obstructs a channel through the body of the plug, or via selection from a choice of available filters or dampers.

A Dutch earplug, Ergotec Varifoon, 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, below 500 Hz the attenuation adjustment range is approximately 20 to 25 dB, 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. At any valve setting the Varifoon provides frequency-dependent attenuation that increases with frequency (see Figure 8).

An example of the selectable-filter design, also manufactured in the Netherlands, is the Elcea custom-molded earplug with a sound channel that is fitted with one of four color-coded filters. Depending on the choice of filter, the attenuation at 125 Hz can be varied from about 8 to 25 dB, with less than 6 dB change in the attenuation for the frequencies at and above 2000 Hz.[26]

There are two important distinctions between passive adjustable-attenuation HPDs such as the Varifoon and passive amplitude-sensitive HPDs, which are discussed next. The former devices require user setting to effect attenuation changes, and the attenuation once selected is essentially independent of incident sound level; whereas the latter (i.e., amplitude-sensitive devices) react automatically to changes in incident sound levels, and the user typically has no control over the change in attenuation. Although the concept of an adjustable-attenuation HPD is appealing, the task of properly matching the HPD attenuation to the user's hearing thresholds and to the environmental noise spectrum, while taking into account communication necessities, is complex. The development of algorithms to facilitate this process is required.

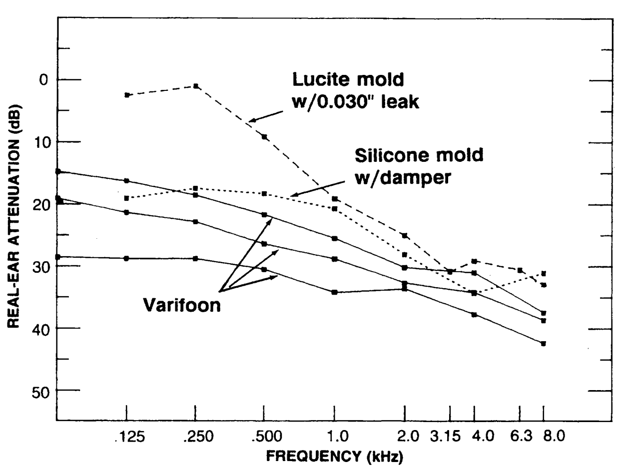

FIGURE 8. Real-ear attenuation at threshold data for custom earmolds with various leakage paths. Ergotec Varifoon is an acrylate custom mold with adjustable valve. Data shown (provided by manufacturer from testing conducted in Germany at the Berufgenossenschaftliches Institut für Arbeitssicherheit) for three valve settings. The silicone mold has an approximate 0.040-inch diameter hole occluded by an acoustical damper. The lucite mold is a standard hearing-aid earmold with a 0.030-inch diameter hole (adapted from Berger).[21]

Amplitude-Sensitive HPDs

As discussed earlier, hearing ability under a conventional HPD is compromised during the quiet periods of intermittent sound exposures because the device yields constant attenuation regardless of ambient noise level. Amplitude-sensitive, also called level-dependent HPDs, reduce this problem by providing diminished attenuation at low sound levels but increased protection at high levels of steady-state and impulsive noise. A dynamically functional valve or round, sharp-edged, or slit-shaped orifice that provides a controlled leakage path into the protector constitutes the nonlinear element that changes attenuation.

The valve-type devices incorporate a diaphragm that purportedly closes off the duct when activated by high sound pressures. However, given the very sharp rise-time profiles of gun blasts and explosive detonations, it is likely that the inertia of the valve will inhibit its closing in time to effect full protection in impulses, and the authors are aware of no published experimental data to demonstrate that such valves perform as sometimes claimed.

On the other hand, the orifice technique has been well-documented both theoretically and empirically.[27] It takes advantage of the nonlinear acoustical behavior that develops when high-level sound (above about 120 dB) attempts to penetrate a small opening.[28] Low-intensity sound waves predominantly exhibit laminar airflow and pass relatively unimpeded through a small aperture, whereas high-intensity waves create a turbulent flow, and as a result incur an excess degree of attenuation due to the aperture's increase in acoustic resistance (the ratio of acoustic pressure across a material to the particle velocity through it) with increasing sound level.

The orifice technique has been applied with success in earplugs, such as the Gunfender, which has been used by the British military for over 20 years[29] and in earmuffs such as the Cabot Safety Corporation Ultra 9000.®[27] The design of the Ultra 9000 places the

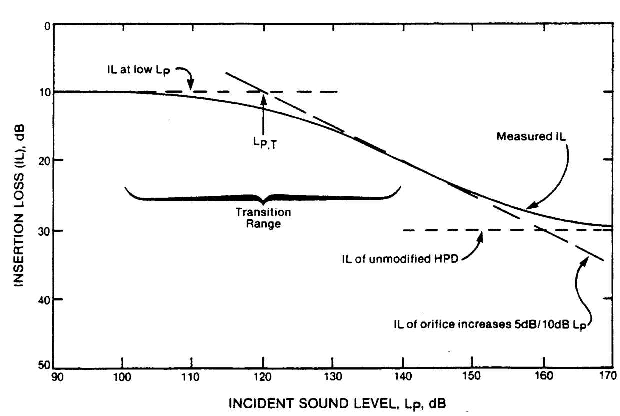

FIGURE 9. Representative insertion loss and illustration of the transition level (L_{PT}) at a single frequency, as a function of incident sound level, for an amplitude-sensitive hearing protector with a nonlinear orifice. The transition range indicates the sound levels at which nonlinearity, due to turbulent flow in the orifice, begins to increase the device's attenuation (adapted from Allen and Berger).[27]

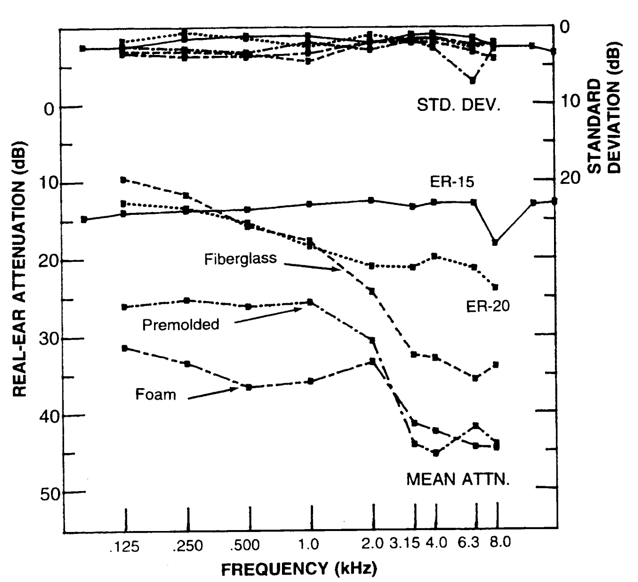

FIGURE 10. Real-ear attenuation at threshold data for three conventional earplugs (user-molded foam, premolded two-flanged earplug, and a fiberglass earplug) and two uniform-attenuation earplugs (custom molded ER-15 and premolded ER-20). The fiberglass earplug is acoustically leaky, which causes its attenuation to slope downward with frequency. The premolded and foam earplugs illustrate the typical attenuation plateau (125 to 2 kHz) representative of conventional earplugs (adapted from Berger).[21]

orifice on the outside of the cup "looking into" a duct that couples to the pinna via a flexibly mounted earpad assembly.

For passive amplitude-sensitive devices a critical performance parameter is the transition sound level at which insertion loss begins to increase. As illustrated in Figure 9, at sound levels beyond the transition sound level insertion loss increases at a rate of up to half the increase in sound level.[21] The increase in attenuation continues to a point where the measured insertion loss approaches that of the equivalent HPD with its nonlinear element sealed shut. At lower but still potentially hazardous sound levels most amplitude-sensitive devices exhibit behavior similar to that of a leaky or vented earplug, affording frequency-dependent attenuation with little noise reduction below 1000 Hz. At least one reported exception is an orifice-type earmuff (Ultra 9000) that provides roughly 25 dB attenuation from 400 to 8000 Hz.[27]

Because passive amplitude-sensitive protectors do not become level-dependent until about 120 dB SPL, they are primarily useful for isolated impulses such as gunfire, especially in outdoor environments.

Certain claims made for purportedly amplitude-sensitive earplugs warrant judicious consideration. For example, one brand of custom-molded vented earplug incorporates an acoustical filter that the manufacturer declares "utilizes the Accelerated Resonance Decay Principle, allowing harmless sound of 80 dB or less to reach the eardrum . . . (but) a jet engine generating 120 dB would be perceived by the ear wearing this earplug as being 80 dB."[21] Another manufacturer presents graphical data showing less than 3 dB attenuation for sounds below 70 dB, but about 20 dB for sound levels of 90 dB (a growth of approximately 0.7 dB/dB increase in sound level).[21]

The claims quoted above imply a rather dramatic level-dependency beginning at or below 80 dB, which is 40 dB less than the previously noted transition level of 120 dB SPL (Figure 9) that marks the onset of nonlinearity for passive nonlinear HPDs. Additionally, the rate of nonlinear growth in attenuation inferred from the above claims is up to twice the rate that is physically possible.[21] While vented earplugs and passive nonlinear HPDs do provide worthwhile performance improvements for certain applications, caution must be exercised in interpreting the available data on certain amplitude-sensitive earplugs.

Uniform-Attenuation HPDs

As depicted by the curves for the foam, fiberglass, and premolded earplugs of Figure 10, conventional earplugs (as well as other types of HPDs) tend to provide increasing attenuation as frequency increases. Therefore, the wearer's hearing of the sound spectrum is distorted. Not only are sounds reduced in level, they are also colored in a spectral sense. Since many auditory cues depend on spectral shape for informational content, conventional HPDs may compromise these cues. For instance, machine tool operators complain that auditory feedback from a cutting tool is distorted, aircraft pilots and tank operators indicate that important signals cannot be discerned, and musicians report pitch perception problems under conventional HPDs. To counter these effects, flat- or uniform-attenuation HPDs, which impose attenuation that is nearly linear from about 100 to 8000 Hz, were developed in the late 1980s (Figure 10).[21] Refinement of these devices, including the offering of models with different attenuation levels, has continued into the 1990s.

Successful flat attenuation inserts have been devised by integrating acoustic elements such as channels, dampers, and diaphragms within custom- or premolded earplugs. One approach, the ER-15 custom-molded earplug as illustrated in Figure 11, utilizes a sound channel as an acoustic mass (inductance, L1), a diaphragm (capacitive element, C1), and a damper (resistive element, R1) to form a resonant system to restore the natural 2.7 kHz resonance of the open ear that is normally lost when the ear is plugged. Another design attribute that flattens the ER-15's response is the placement of the plug's sound inlet in close proximity to the entrance of the ear

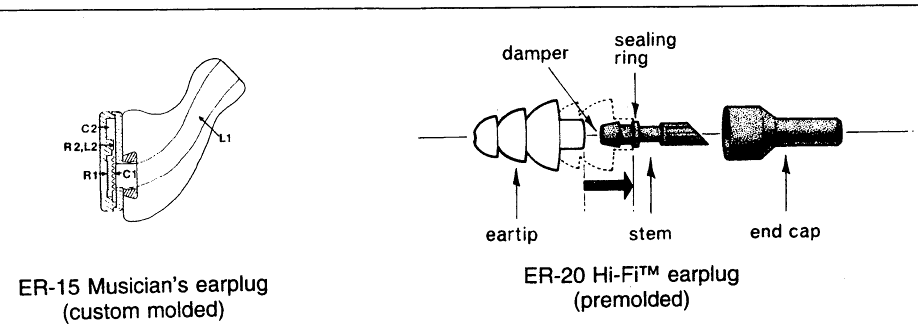

FIGURE 11. Illustration of the construction features of two flat-attenuation earplugs. The ER-15 includes resistances R1 and R2, capacitances C1 and C2, and inductances L1 and L2. L1 is a sound channel through the custom earmold that is capped at its outer end by a plastic button assembly containing the remaining acoustical elements. The ER-20 also utilizes a sound channel, but only a single resistive element (labeled "damper" in the figure).Section 2

canal to take advantage of the natural high-frequency amplification of the pinna/concha. This causes more sound energy to enter the inlet, effectively reducing the plug's attenuation. This combination of features results in a flat attenuation profile of about 15 dB across frequencies.[30] An alternative version providing flat attenuation of about 25 dB is also available.[31]

An alternative, substantially less expensive earplug design, which incorporates its acoustical elements into a premolded earplug body, is the Cabot Safety ER-20 Ultra-Tech earplug. In this case the diaphragm is replaced with an acoustical damper, and the pinna/concha sound pickup is effected via a folded horn assembly that caps the open end of the earplug (Figure 11). Although a relatively flat attenuation profile is obtained, the performance is not quite as uniform as the ER-15 (Figure 10).

Although anecdotal and theoretical evidence abounds, empirical studies proving the aural benefits of uniform-attenuation HPDs are as yet lacking. Nevertheless, better hearing perception and adequate protection should be achievable with properly fitted uniform HPDs in low to moderate noise exposures of about 90 dBA or less. Professional musicians and individuals with high-frequency hearing loss may find such devices particularly beneficial. However, for noises having substantial high-frequency energy, uniform attenuation earplugs generally offer less protection than conventional custom-molded or premolded earplugs, as shown in Figure 10.

CONCLUSION

This review has examined specialized types of HPDs of both the active (electronic) and passive (nonelectronic) varieties. In situations where speech communication, aural signal detection, and/or sound interpretation is an issue, or where the listener has an existing hearing impairment, the industrial hygienist or safety engineer should consider the potential disadvantages posed by conventional passive HPDs and investigate alternative devices that incorporate special features to augment hearing acuity while still providing satisfactory protection.

The active and passive designs can provide valuable performance advantages to potentially ameliorate situations such as employees needing less attenuation to hear well, overcoming the spectral distortion typical of conventional HPDs, or providing attenuation that dynamically changes with sound level. In fact, active designs, including the ANR and sound transmission varieties, are among the most publicized HPDs sold today. However, these new devices are not a panacea. None are perfect or suited to all applications.

When considering specialized HPDs, account must also be made of their increased costs and potential reduced reliability compared with the conventional HPD alternatives. In many instances it may be required in occupational hearing conservation programs that certain problem situations or difficult-to-fit employees will be issued specialized devices, whereas the majority of the work force will be dispensed the lower-cost conventional devices that are sufficient for their needs.

Consensus standards need to be developed to guide the testing of active as well as passive amplitude-sensitive HPDs to better quantify their unique performance characteristics. Without data from such standards, the hearing conservationist has little objective basis on which to make an informed decision concerning device selection. Also, further research is required to determine both the real-world attenuation and the speech intelligibility/auditory performance with these augmented HPDs, and the degree to which such devices can assist in resolving the numerous issues facing today's hearing conservationist.

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