EARLOG 5

Fifth in a comprehensive series of technical monographs covering topics related to hearing and hearing protection.

Hearing Protector Performance: How They Work - and - What Goes Wrong in the Real World

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In previous EARLogs[1] we have discussed how to measure and rate the attenuation of hearing protection devices (HPDs) in the laboratory, how these devices affect auditory communications, and perhaps most importantly how HPDs perform in real world (RW) environments. It was found that laboratory attenuation measurements significantly overestimate the RW performance of HPDs, due to the unrealistic, optimized manner in which experimental subjects can wear these devices for short duration tests. In this, EARLog #5, we will examine these concepts further by analyzing how a correctly worn HPD operates and how its effectiveness is compromised by misuse, misfitting, HPD aging, and abuse.

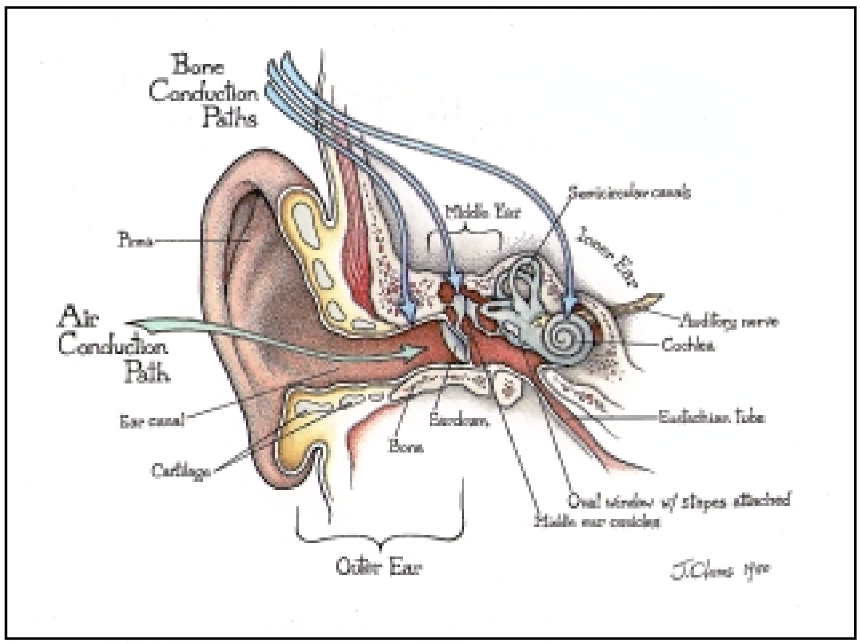


FIGURE 1. Basic Anatomy of the Ear with Illustration of the Air Conduction and Bone Conduction Sound Paths.

Sound Transmission to the Unoccluded Ear

The hearing mechanism can be divided into three parts as shown in Figure 1. These are the outer, middle and inner ear. Sound (airborne vibration) is received by the outer ear. The incident sound propagates along the auditory canal, setting the eardrum (tympanic membrane) into motion. The eardrum motion is transmitted via the tiny middle ear bones (ossicular chain) to the inner ear, a liquid filled cavity of complex shape lying within the bony structure of the skull. This causes the liquid in a portion of the inner ear, the cochlea, to vibrate. Membranes and hair cells inside the cochlea, which are very sensitive to this vibration, generate electrical impulses when appropriately stimulated. The impulses are transmitted along the auditory nerve to the brain, where they are "decoded ". The result is the sensation, sound.

When the vibration that excites the cochlear hair cells is the result of the chain of events described above, this is called air conduction. When sound directly vibrates the skull and/or excites vibration of the ear canal walls which in turn stimulates the cochlea, it is called bone conduction. The final sense organ, the cochlea, is the same in either case, only the path of excitation has changed. Since most sound and/or vibration sources will excite both transmission paths, the ear will usually receive both air conducted and bone conducted signals simultaneously.

For the normal hearing individual, the unoccluded ear's bone conduction (BC) sensitivity is much poorer than its corresponding air conduction (AC) sensitivity as shown in Figure 2, curve A. For example at 1000 Hz the sensitivity of the ear is 60 dB poorer for the BC path than for the AC path. This means that even if the AC path were totally eliminated by a HPD, that the ear's sensitivity would only be approximately 60 dB worse, i.e. a "perfect" HPD could only offer 60 dB of attenuation at 1 kHz. Even if the entire head was acoustically shielded, the loudness level of the sound would only

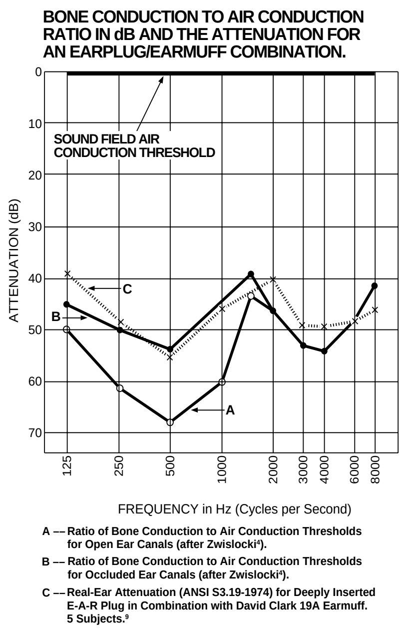


Figure 2

be reduced by an additional 10 dB to ≅ 70 dB below the unoccluded AC threshold.[2] In this latter case, the conduction path would be from the chest cavity thru the neck to the head.

Sound Transmission to the Occluded Ear

The utilization of a HPD modifies the AC and BC paths discussed in the previous section. Four distinct sound pathways can now be distinguished as shown in Figure 3. There are:

1. Air Leaks - For maximum protection the device must make a virtual air tight seal with the canal or the side of the head. Inserts must accurately fit the contours of the ear canal and earmuff cushions must accurately fit the areas surrounding the external ear (pinna). Air leaks can typically reduce attenuation by 5-15 dB over a broad frequency range.[3]
2. Vibration of the HPD - Due to the flexibility of the ear canal flesh, earplugs can vibrate in a piston-like manner within the ear canal. This limits their low frequency attenuation. Likewise an earmuff cannot be attached to the head in a totally rigid manner. Its cup will vibrate against the head as a mass/spring system, with an effective stiffness governed by the flexibility of the muff cushion and the flesh surrounding the ear, as well as the air volume entrapped under the cup. For earmuffs, premolded inserts and foam inserts these limits of attenuation at 125 Hz are approximately 25 dB, 30 dB and 40 dB, respectively.
3. Transmission thru the Material of the HPD - For most inserts this is generally not significant, although with lower attenuation devices such as cotton or glassdown, this path is a factor to be considered. Because of the much larger surface areas involved with earmuffs, sound transmission thru the cup material and thru the earmuff cushion is significant, and can limit the achievable attenuation at certain frequencies.
4. Bone Conduction - Since a HPD is designed to effectively reduce the AC path and not the BC path, BC may become a significant factor for the protected ear.

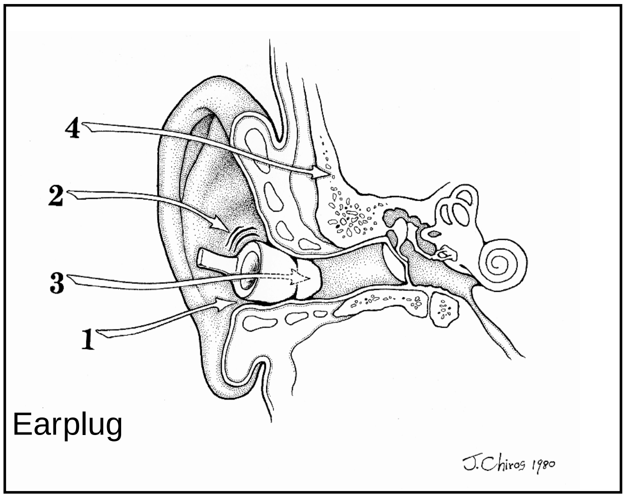
When the ear is occluded with an insert or a muff the BC path is enhanced relative to the unoccluded ear for frequencies below 2 kHz. This is called the earplug effect [4, 5] or more generally the occlusion effect.[6,7] This can be easily demonstrated by plugging one's ear canals while speaking aloud. When the canals are properly sealed or covered, one's own voice takes on a bassy, resonant quality due to the amplification of the BC path by which a talker partially hears his own speech. This amplification of BC vibrations results in the differences between curves A and B in Figure 2. Curve A represents the threshold of hearing for BC vibrations with open ear canals, whereas curve B is the threshold of hearing for BC vibrations with the ear canals tightly covered or plugged. *Thus, curve B gives the estimated maximum protection achievable by covering and/or plugging the ears.*

A common myth concerning HPDs is that as the sound level increases BC sound becomes more important, and therefore an earmuff will provide better protection than an earplug at higher sound levels. The inaccuracy of this statement is demonstrated by the fact that the relationship between the AC and BC thresholds, as shown in Figure 2, is not dependent on sound level. Any BC advantage that muffs may have over inserts will be independent of sound level, and will be apparent in a standard threshold level attenuation test such as ANSI S3.19-1974.

Due to the occlusion effects and BC limitations described above, as well as other physical considerations, using muffs and inserts in combination does not yield attenuation values that are merely the arithmetic sum of their individual values. In some cases, at some frequencies, almost no improvement will be noted when inserting a pre-molded insert under a muff.[8] Alternatively for other combinations, not fully defined at this time, better results may be achieved. Curve C in Figure 2 demonstrates performance for a deeply inserted E-A-R Plug used in conjunction with a David Clark 19A earmuff.[9] This combination probably represents the highest practical attenuation achievable with currently available HPDs.

Why HPDs Fail in the Real World

When a HPD is properly sized and carefully fitted and adjusted for optimum performance on a laboratory subject, air leaks will be minimized and paths 2, 3 and 4 will be the primary sound transmission paths. In the RW work environment, this is usually not the case, and path 1, sound transmission thru air leaks, often dominates. Air leaks arise when plugs do not seal properly in the ear canal or muffs do not seal uniformly against the head around the pinna. The causes of poor HPD sealing are:



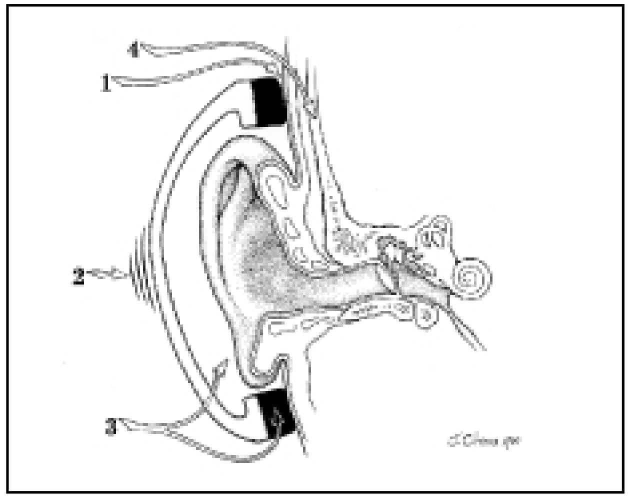


FIGURE 3. Illustrations of the 4 Paths by Which Sound Reaches the Occluded Ear.

1. Comfort - In most situations the better the fit of a HPD, the poorer the comfort. Inserts must be snugly fitted into the canal and earmuff cups must be tightly pressed against the head. This is not conducive to comfort and although some employees may adapt, many will not. This is why it is important to select several hearing protectors (generally 1 muff and 2 earplugs) from the more comfortable available HPDs and to encourage the employee to make the final decision as to which he will use.

2. Utilization - Due to poor comfort, poor motivation or poor training, or user problems, earplugs may be improperly inserted and earmuffs may be improperly adjusted.

3. Fit - All HPDs must be properly fitted when they are initially dispensed. For multi-sized premolded inserts a suitably sized earplug must also be selected during this fitting procedure. Companies must stock all available sizes of multi-sized earplugs and must be willing to use different size plugs for an employee's two ears, this latter situation occurring in perhaps 2-10% of the population. For example, stocking only 3 of the 5 available sizes of the V51-R will reduce the percentage of the population fitable with that device from $\cong$ 95% to $\cong$ 85%. The correct size pre-molded insert will always be a compromise between a device that is too large and therefore uncomfortable, and a device that is too small and therefore provides poor protection. The appropriate compromise can often times be achieved, but only with care and skill.

4. Compatibility - Not all HPDs are equally suited for all ear canal and head shapes. Certain head contours cannot be fitted by any available muffs and some ear canals have shapes that may only be fitable with certain inserts or canal caps or sometimes not at all. Earmuffs can only work well when their cushions properly seal on the head. Eyeglasses, sideburns, or long or bushy hair underneath cushions will prevent this and will reduce attenuation by varying amounts.

5. Readjustment - HPDs can work loose or be jarred out of position during the day. It must be remembered that laboratory tests require the subject to carefully adjust a device prior to testing. Under typical use, wearers will eat, talk, move about and may be bumped or jostled, resulting in jaw motion and possible perspiration. These activities can cause muff cushions to break their seal with the head and cause certain inserts to work loose.[10,11] Premolded inserts tend to exhibit this problem, whereas custom molded and expandable foam plugs tend to more effectively maintain their position in the ear canal.

6. Deterioration - Even when properly used, hearing protectors wear out. Some pre-molded plugs shrink and/or harden when continuously exposed to ear canal wax and perspiration. This may occur in as little as three weeks. Flanges can break off and plugs may crack.[12,13] Custom earmolds may crack, or the ear canal may gradually change shape with time, so that the molds no longer fit properly. Earmuff cushions also harden and crack or can become permanently deformed and headbands may lose their ten-

TIME-CORRECTED NRR AS A FUNCTION OF WEARING TIME (USING OSHA 5 dB TRADING RELATIONSHIP).

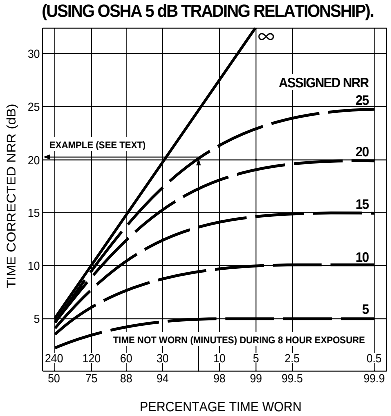


Figure 4

sion. Therefore it is important to inspect or reissue ‘’permanent’’ HPDs on a regular basis. This may be 2-12 times per year or more, depending upon the HPDs that are utilized.

7. Abuse - Employees often modify HPDs to improve comfort at the expense of protection.[12,13,14] These techniques include springing earmuff headbands to reduce the tension, cutting flanges off of premolded inserts, drilling holes thru plugs or muffs, removing the canal portion of custom earmolds, or deliberately obtaining undersized HPDs.

Protection vs. Percentage Time Worn

The HPD RW utilization problems outlined in the preceding section explain why the RW attenuation of HPDs is so much lower than typical manufacturers' laboratory data would indicate (as was extensively discussed in EARLog # 4[1]). In addition to this problem we must contend with the possibility that employees, regardless of how well they wear an HPD, may not wear it during their entire work-shift or period of noise exposure. This will reduce their effective daily protection.

Noise induced hearing loss has been shown to be a function of the cumulative A-weighted noise exposure incident upon the ears.[15,16] Adherents of this theory propose that the hearing levels of a noise exposed population can be estimated from a knowledge of their equivalent continuous noise exposure level (L_{eq}). The L_{eq} is the level of continuous A-weighted noise that would cause the same sound energy to be experienced in an 8-hour day, as resulted from the actual noise exposure. This leads to the 3 dB trading relationship, that is, if the exposure level is increased by 3 dB, the exposure duration must be reduced by 1/2. A similar approach is embodied in the U.S. Occupational Safety and Health Act[17], except that the trading relationship is 5 dB. The implications of the cumulative energy theory with regards to the protection afforded by HPDs, were first discussed by Else.[18] They are presented graphically in Figure 4, with suitable modifications to conform with the OSHA 5 dB trading relationship.

The data in Figure 4 can be utilized to determine the Time Corrected Noise Reduction Rating (NRR) as a function of the percentage of time that the HPD is worn in the noise. We first assign an NRR value to the HPD in question - either the manufacturers' labeled NRR or preferably a RW estimated NRR. If, for example, the HPD had an assigned NRR = 25, then its Time Corrected NRR would be only 20 dB if it was not worn for just 15 minutes during each 8 hour noise exposure. This clearly demonstrates that HPDs must be comfortable enough to be worn properly for extended periods. Attenuation and comfort must both be considered when selecting an HPD.

Neither low attenuation nor low comfort devices are acceptable for standard industrial use. Comfortable, user acceptable HPDs, with real world NRRs suitable for the prevailing environmental sound levels will be necessary to protect your employees' hearing.

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