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

BY ELLIOTT H. BERGER
Senior Scientist, Auditory Research

In previous EARLogs\textsuperscript{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.

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 excites 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
2. Vibration of the HPD - Due to the

In this latter case, the conduction

be reduced by an additional 10 dB to =

70 dB below the unoccluded AC thresh-

3. Transmission thru the Material of the

HPD - For most inserts this is gen-

eral 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 in-
volved with earmuffs, sound trans-
mision thru the cup material and
thu the earmuff cushion is signifi-
cant, and can limit the achievable at-
tenuation 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 in-
sert or a muff the BC path is enhanced
relative to the unoccluded ear for fre-
cuencies below 2 kHz. This is called
the earplug effect 4, 5 or more gener-
ally 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 cov-
ered, one's own voice takes on a bassy,
resonant quality due to the amplifica-
tion 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 vibra-
tions 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 bet-
ter 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 Fig-
ure 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 in-
dividual values. In some cases, at
some frequencies, almost no improve-
ment will be noted when inserting a
pre-molded insert under a muff. 4 Alter-
natively 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 attenu-
ation achievable with currently avail-
able HPDs.

Why HPDs Fail in the Real World

When a HPD is properly sized and
carefully fitted and adjusted for opti-
mum performance on a laboratory sub-
ject, 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 transmis-
sion 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 pre-molded 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 = 95% to = 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. Pre-molded 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. 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-
Employees often modify 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. These techniques include springing earmuff headbands to reduce the tension, cutting flanges off of pre-molded 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’). 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. 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 background 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 Act17, 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.

References and Footnotes

1. Berger, E.H. - The EARLog series is available upon request from Aearo Company.
9. Data from E-A-RCALM Laboratory experiments in progress.