Empirical Evaluation using Impulse Noise of the Level-Dependency of Various Passive Earplug Designs

E-A-R 07-38/HP

E. H. Berger, M.S.[1]
P. Hamery, Ph D.[2]

[1]3M
E•A•RCAL℠ Laboratory
7911 Zionsville Road
Indianapolis, IN 46268-1657
phone: 317-692-3031
Elliott.Berger@mmm.com

[2]Institute of Saint-Louis (ISL)
5 rue du General-Cassagnou
St. Louis, France F68301
phone: (33) 3-8969-5095
email: hamery@isl.tm.fr

Originally Published June 23, 2008
Revised January 4, 2010

Version 4.2

Presentation at Acoustics ’08 Paris, June 29 – July 4, 2008
J. Acoust. Soc. Am. 123(5, Pt. 2), p. 3528.

An objective in the development of hearing protection devices (HPDs) has been the design of a passive earplug that provides modest or no attenuation at low sound levels, with greater protection at high sound levels. This raises the issue of not only how to construct such a device, but also how to evaluate it. There is the related question of whether conventional HPDs are actually level independent. Passive level dependency is typically accomplished via an orifice that causes sound transmission to decrease as input level increases. We utilized an impulsive noise source (explosives) with peak levels from 110 to 190 dB SPL to measure the insertion loss of a variety of commercially available and developmental earplugs. The tests were conducted at frontal incidence over a reflecting plane outdoors using the Institute of Saint-Louis acoustical test fixture specifically constructed for HPD attenuation measurements. Conventional foam and premolded earplugs exhibited attenuation that was essentially constant with level, whereas the best of the level-dependent designs provided attenuation that increased by about 25 dB over the 80-dB range of test impulse levels. This latter design has been successfully utilized since 2000 in the Combat Arms® Plug widely fielded in the U. S. Military.

1 Introduction

It is commonly observed that the correct and consistent use of hearing protection devices (HPDs) with adequate noise reduction can prevent the occurrence of virtually all noise-induced hearing loss. However, an obvious problem can occur in the presence of an impulsive noise source for which the hearer has no warning and thus has not donned hearing protection. A useful improvement, especially in military operations, is an HPD that provides sufficient protection from the unexpected blasts, yet can be worn at all times when potential auditory danger is present without impeding acoustic perception, commonly called situational awareness in military parlance. It is possible to design an electronic product with such features, essentially a hearing aid at low levels with compression of higher level sounds, altogether another matter to accomplish this in a passive design, perhaps with moving parts, but no energy input besides that provided by the incoming sound or blast wave.

Since at least the 1960s the concept of a level-dependent (sometimes called "nonlinear") orifice in an earplug or earmuff has been explored.[1, 2] One of the early researchers of such ideas, Clay Allen, developed the concept into a level-dependent earplug design, further examined by Forrest,[3] and marketed as the Gunfender, by Racal Safety Ltd. Additional passive designs have been introduced over the years including the well-known Lee-Sonic Ear Valv (which became the North Sonic Ear Valvs® in various versions), the Aural Technology Protectear™, and the Hocks Noise Braker. In the 1990s work began and was reported by the Institut of Saint Louis (ISL) on nonlinear orifices that led to an improved design embodied in the Combat Arms Earplug and other versions, as described more fully later in the report.

The Ear Valv design has employed over the years various types of valves, more recently diaphragms, that are intended to both move and close in response to high-level sound, thus providing substantially augmented protection. Although these designs do appear to provide a measure of level dependency, no data on the existing designs has been forthcoming that would suggest that the valve actually moves sufficiently to close down. The Protectear and Noise Braker approach is to use a constricted channel through an orifice which purports to utilize the "accelerated resonance decay principle" so that no sounds over 80 dB are allowed to pass through the filter.[4] Such extravagant claims have never been adequately documented and are at odds with the accepted theoretical understanding of level-dependency caused by nonlinearity in small orifices.[5,6]

Despite high interest in passive amplitude-sensitive earplugs and strong claims made by some manufacturers regarding their performance, sparse data are available in the literature. This is probably due in part to the difficulty of measuring the performance of these products. An early study using cadavers as acoustic test fixtures for objective measurements demonstrated level dependency for the Gunfender and Lee-Sonic products.[7] Several well-controlled studies using human subjects exposed to weapon's fire and explosives have also been reported in the literature and demonstrate the protectiveness of perforated, presumably level-dependent earplugs and earmuffs for such noises.[8-10] However, we are unaware of any studies that have comprehensively examined the measured attenuation of a wide variety of purportedly level dependent HPDs over a range of sound levels from threshold to 190 dBP SPL; hence the need for this study.

2 Passive level dependency – theoretical background

Level dependency in passive hearing protectors may cause either an increase or decrease in attenuation with increasing sound level. Clearly the former is preferred, but the latter may be observed when for example a blast is sufficiently intense that the induced motion in the earplug or earmuff causes it to momentarily or permanently lose its acoustic seal. On the other hand, increasing attenuation, a positive feature in HPD design, has been theoretically and empirically demonstrated with narrow sharp-edged orifices as noted above.

The attenuation of the orifice can be thought of as a resistive element that is the ratio of the acoustic pressure in the orifice to the particle velocity through it. At low sound levels, streamlined airflow predominates and the pressure is therefore linearly related to the particle velocity. However, at sufficiently high levels turbulence occurs as vortexes are generated at the exit of the orifice, and the pressure then becomes proportional to the square of the particle velocity and the resistance increases. A detailed analysis can be found in [6].

A key point is that in such designs the level-dependency arises due to an orifice, which at levels below where its amplitude sensitivity becomes apparent, is effectively an acoustic leak that degrades attenuation of the basic passive device, were the hole not present. Thus, the level-dependent increase in attenuation does not and cannot increase the attenuation over that of the basic passive HPD with the hole sealed shut, rather it serves to decrease the loss in attenuation caused by the orifice at low sound levels. Level dependency only becomes apparent as the sound level increases above a transition level at which the turbulence appears.

The most effective passive orifice designs to date demonstrate level dependency first occurring around 110 to 115 dB SPL.[6] Once level dependency is initiated, the maximum theoretical rate of increase is 0.5-dB-per-decibel increase in sound level above the critical transition level.

3 Procedures

In order to benchmark the attenuation of the devices in this study, they were evaluated by the first author using the standardized method of real-ear attenuation at threshold. Since such measurements are conducted at relatively low sound levels within 40 to 50 dB of the hearing threshold levels of normal-hearing subjects, these data represent the low-sound level attenuation of the HPDs in this study, at levels well below the transition region.[11]

Procedures that have typically been utilized for the measurement of level-dependent attenuation include microphone-in-real ear (MIRE) measurements and the use of acoustical test fixtures (ATFs). Both are objective procedures that can be implemented at sound levels well above threshold, and hence can be used to explore attenuation at and above the transition sound pressure level. The ATF procedure for the studies reported herein was implemented by the second author.[11]

Both the real-ear attenuation at threshold (REAT) and ATF procedure are described in greater detail below.

3.1 Real-ear attenuation at threshold (REAT)

REAT was measured in the E•A•RCAL[SM] facility of Aearo Technologies according to ANSI S12.6-1997 (R2002).[12] Depending on the device, the subject count and measurements per subject was either 10 x 3 or 5 x 2, versus the 20 x 2 that is called for in S12.6. Another variance from the standard was the exact method of fitting the HPD, although the procedure utilized closely mimicked Method A of the standard. The goal was to make sure the devices were well fitted so that the leakage path controlling the attenuation and also potentially behaving in a level-dependent manner was the intentional one, normally an orifice, and not a leak around the earplug itself.

3.2 Acoustical test fixture measurements

The ATF that was utilized was designed and constructed by ISL.[13] Tests were conducted outdoors above a reflecting plane using impulse noises created at the lowest sound level by gunfire and at increasing levels by a detonator, primer, or C4 explosives. The test noise spectra are shown in Fig. 1. Sounds were incident on the ATF at frontal incidence (grazing incidence to the distal end of the earplugs).

Sound levels were simultaneously measured outside the ear of the test fixture and at its "eardrum." Those data provided noise reduction values that were then converted to insertion loss by use of the transfer function of the open ear (TFOE) of the ATF. Details of the ISL test procedures can be found in [6].

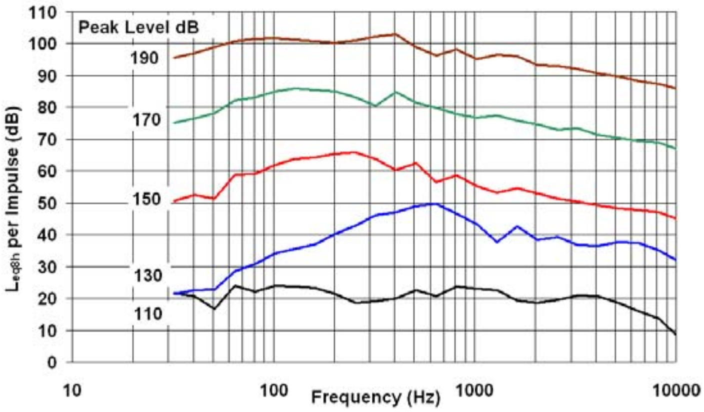

Fig. 1 - Spectra of the impulses used for testing.

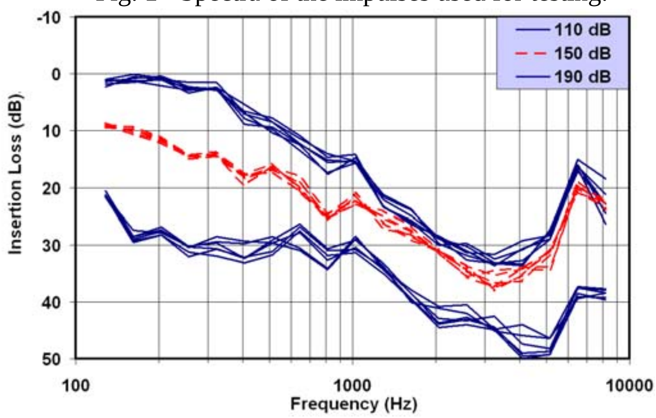

Fig. 2 – Repeatability of IL measurements on one sample Combat Arms Earplug measured 8 times over 2-yr. time frame.

An indication of the repeatability of the measured data can be gleaned from Fig. 2. These data represent 8 measurements on four samples of the Combat Arms Earplug over a two-year period. These are the raw ATF insertion-loss values without the corrections described in the next paragraph. The range in values over the eight measurements is 2 – 3 dB at each frequency regardless of impulse level.

The ATF utilized had inherent insertion loss values of at least 65 dB from 80 Hz to 10 kHz, which exceeds the bone- and tissue-conduction (BC) limits to the human skull. This assures that its measurements were not contaminated by its own "BC" pathways. On the other hand, this means that larger values of insertion loss can be measured on the ATF than can actually be realized on human heads. Therefore, the data were computationally corrected by presuming a BC pathway in parallel with the sound-conduction pathway through the HPD. The BC values are based upon the data from Berger et al.[14] The values were also adjusted by the magnitude of the occlusion effect as observed in REAT testing in order to make the ATF-measured data correspond as closely as possible with REAT values. This was a 2-dB correction at 125 Hz, decreasing to 0 dB at 250 Hz.

In addition to the impulse noise measurements, steady-state measurements were also conducted using the ISL ATF in an 85-dBA reverberant quasi-diffuse sound field in order to characterize the performance of the level-dependent devices at sound levels below the transition region.

3.3 Product test samples

The earplugs evaluated in this study are shown in Fig. 3 and listed, along with a description of their level-dependent elements, in Table 1. The level-dependent data described herein for the dual-ended Combat Arms earplug have been found to also describe the simpler single-ended version also containing the ISL filter in the stem of a premolded UltraFit™ earplug as well as to the most recent single-ended design, also with an ISL filter that uses a selector dial.

Figure 3 – Earplugs tested in this study as described in Table 1. Gunfender (back and front view), Combat Arms, Noise Braker, Ear Valvs, Sound Baffler, and Quiet Please (left to right, top to bottom).

Earplug	Description of level-dependent element
Amplivox Gunfender	metal disc with 0.6-mm ID hole
E•A•R™ Combat Arms Earplug	ISL filter with 0.3-mm ID hole at each end
Hocks Noise Braker® earplugs	tapered 5.5-mm tube; ID varies from 0.3 to 0.9 mm
North Sonic Ear Valvs® earplugs	rubber diaphragm between metal plates
Silencio® Super Sound Baffler	rubber diaphragm between metal and plastic plate
Tico Quiet Please	sintered metal and fabric filters

Table 1 – Earplugs tested in this study

4 Results

The earplug that we have studied most thoroughly is the Combat Arms plug with the ISL filter. That filter, consisting of a small plastic canister with 0.3-mm inside diameter (ID) holes at each end has been imbedded in the stem of various versions of the UltraFit® earplugs, both dual-ended (as shown in Fig. 3) and single-ended designs. We begin by reporting data graphically in Fig. 4, for the dual-ended version of that product as illustrated in Fig. 3.

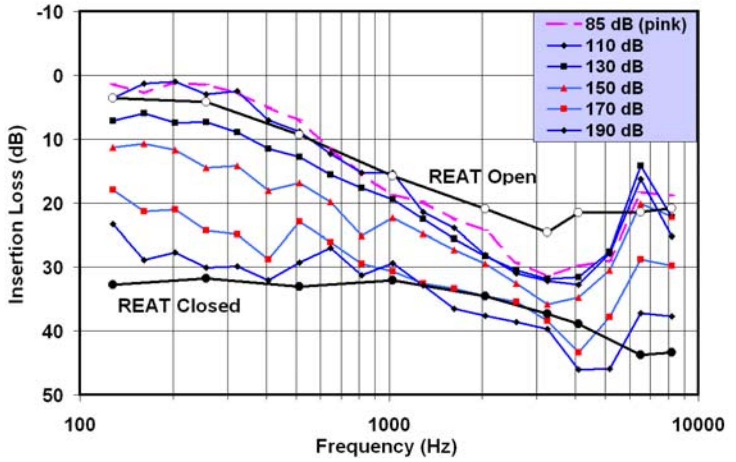

Fig. 4 – IL for the Combat Arms Earplug over an 80-dB range in impulse sound levels and for steady 85-dB pink noise as compared to REAT measurements for the open and closed orifices.

The dashed line shows the IL (corrected for BC and occlusion effect) in 85-dBA pink noise as compared to the IL for five levels of impulses from 110 to 190 dB peak SPL. Note the close comparison of the IL in pink noise and for the 110-dB impulse (both measured in the same ATF). This indicates the same amount of attenuation regardless of steady or impulsive sounds as long as the input levels are the same. The IL then grows substantially as levels increase above 110 dB.

REAT curves (human-subject data) are superimposed in Fig. 4. Ideally the REAT-open curve (meaning that the level-dependent orifice is open and exposed to the sound field) would match the pink-noise curve. The agreement is within a few dB except from 2 – 4 kHz where the ATF values are higher by as much as 7 dB. This may be due to the different sound fields and to the ATF not exactly modeling real-ear performance.

The REAT-closed values are measured with a sealed orifice. They represent the maximum IL possible for these tests with this particular plug style. Thus, the level-dependent attenuation with the orifice open would not be expected to exceed those values since the best the level-dependent orifice can do is behave as though it were closed. The data in Fig. 4 confirm this supposition except from 2 – 4 kHz where the level-dependent performance exceeds the expected values, likely due to the same ATF- and sound-field related issues described in the prior paragraph.

The data for the Gunfender are shown in Fig. 5. This is a "classic" level-dependent orifice design and as Allen and Berger[5] reported previously it is indeed level dependent. As in Fig. 4 the pink-noise and 110-dB impulse data closely align and this time the REAT-open values are in reasonable agreement, too.

A final example is shown in Fig. 6 for the Noise Braker earplug. This too is an orifice design, but this time a tapered tube. In the high frequencies the agreement between the pink-noise and 110-dB impulse curves is off by about 4 dB at 4 kHz, but is in closer agreement at 8 kHz.

There is also an unexplained divergence between the pink-noise and REAT values at a number of frequencies. Though the Noise Braker does show level-dependent behavior, there is no indication that it conforms to the product claims of sudden increase in attenuation for input levels above 80 dB.

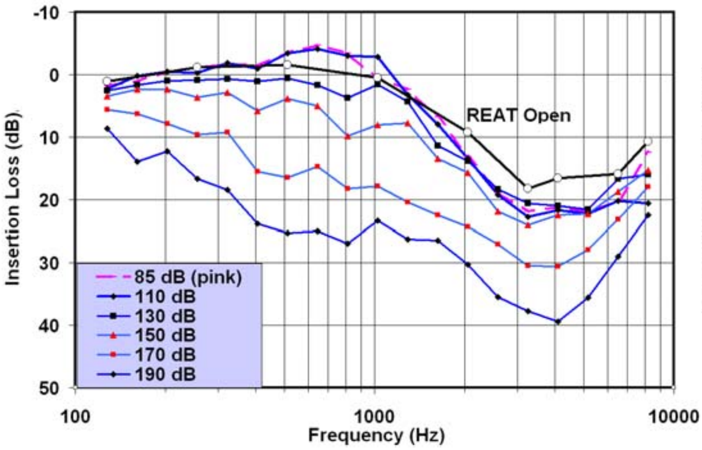

Fig. 5 – IL for the Gunfender earplug over an 80-dB range in impulse sound levels and for steady 85-dB pink noise as compared to REAT measurements for the open orifice.

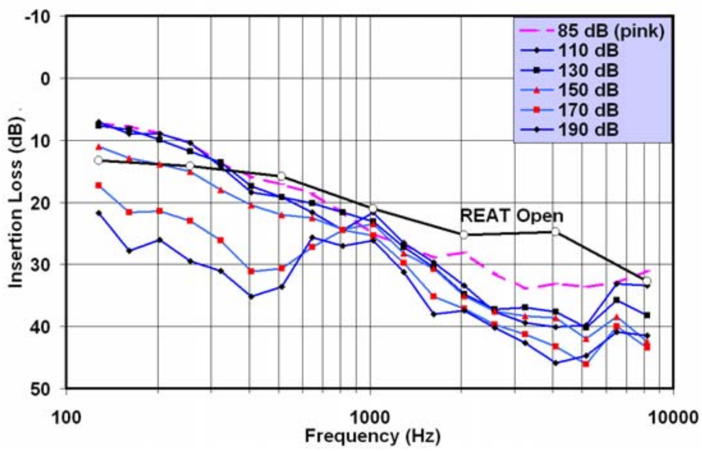

Fig. 6 - IL for the Noise Braker earplug over an 80-dB range in impulse sound levels and for steady 85-dB pink noise as compared to REAT measurements for the open orifice.

Though space does not permit presenting the data, similar analyses were completed for the other products listed in Table 1. The results for all of the earplugs are summarized in a different format in Fig. 7 where the computed overall noise reduction of the impulses is presented as a function of the impulse level. These values are computed like the Noise Reduction Rating (NRR)[15] used in the U. S. with a standard deviation of 4.0 dB at all frequencies, representative of the variability found in REAT evaluations of these types of plugs.

The data in Fig. 7 indicate that all of these purportedly level-dependent earplugs do provide a measure of level dependency. Though theory suggests that a rate of increase in attenuation of 0.5-dB-per-dB increase in sound level is achievable, the best in practice is 0.25-dB-per-dB as can be noted by comparison to the dashed curve in Fig. 7. Some, like the Noise Braker, show only a slow growth at first, and then increase closer to the 0.25-dB rate at the sound levels increase. Others, like the Gunfender, provide a uniform increase over the range, but start out with so little attenuation initially at the low frequencies (see Fig. 5) that the overall noise reduction is less than or equal to 0 dB until the impulses exceed 150 dB. The Combat Arms Plug provides a uniform increase over the entire range with level-dependency first occurring at or above 110 dB.

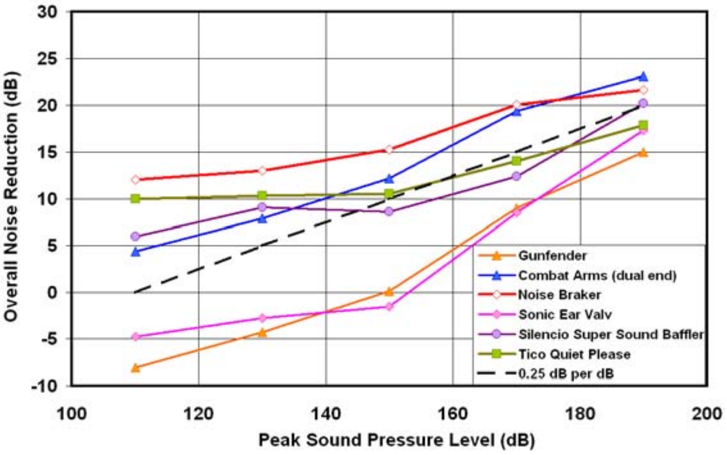

Fig. 7 – Overall noise reduction (computed like the Noise Reduction Rating, but using an assumed standard deviation of 4.0 dB at all frequencies) as a function of peak SPL, for six level-dependent earplugs as compared to a uniform increase of 0.25 dB per dB increase in SPL.

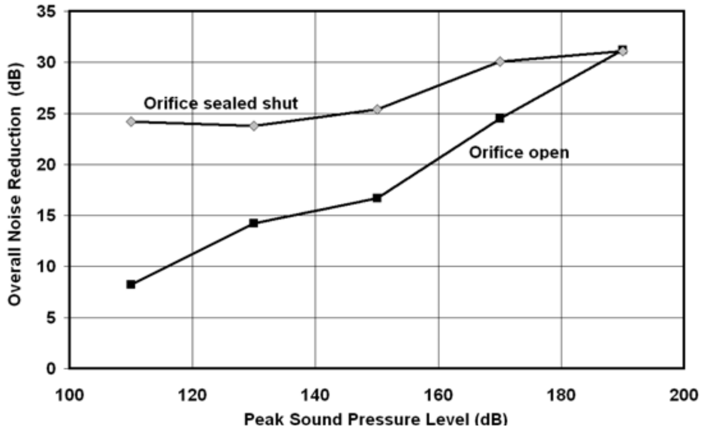

Fig. 8 – Overall noise reduction as a function of peak SPL for an orifice-type level-dependent earplug with the orifice open or sealed shut.

As a test of the measurement system and to research the possibility that all types of earplugs would behave nonlinearly and afford level-dependent protection at very high sound levels, a number of tests were conducted on plugs that would be expected to provide level-independent attenuation. One such test is presented in Fig. 8 for the Combat Arms Earplug open and sealed shut. Though there is some evidence of level dependency in the sealed orifice it is substantially less than with the open orifice. The agreement between the attenuation for the open and sealed orifices at the highest test levels, 190 dBP, can also be seen in Fig. 4, as was previously discussed.

Additional tests of a conventional premolded and foam earplug were also conducted. Though the data are not reported herein, those devices were found to provide insertion loss that was substantially independent of incident sound level with slight or marginal changes (about 5 dB) in attenuation seen at some frequencies over a wide range of sound levels. This type of performance would be expected for an imperforate hearing protector unless the sound levels or blast exposures were sufficient to dislodge the seal of the product.

5 Conclusion

A variety of purportedly level-dependent as well as conventional intentionally level-independent earplugs were evaluated. Procedures included subjective REAT to establish the attenuation of the devices at low sound levels and in real ears, and an objective ATF procedure accomplished with both moderately high-level (85-dB) pink noise as well as noise impulses from 110 to 190 dB SPL. All of the devices that were designed to be level dependent included an orifice or valve assembly, and all of them indeed exhibited level-dependent behavior of varying magnitudes. The earplug showing the greatest level dependency over the range of impulse levels tested, the Combat Arms Earplug, provided an increase in attenuation of 19 dB overall reduction (25 dB in the peak levels) over the 80-dB range of sound levels that were tested. Such designs have been shown in human-subject studies to improve situational awareness over standard earplugs, and yet provide sufficient protection from weapons fire in most situations.[8, 10]

By contrast representative premolded and foam earplugs devoid of orifices were also evaluated and found to provide attenuation that was substantially independent of sound level. This was also illustrated on a level-dependent earplug that was evaluated with its orifice open and functioning vs. sealed shut.

Though level-dependent behavior was observed, it was not of the dramatic type that has been claimed to occur for certain passive valve- or orifice-based earplugs in which attenuation would supposedly change dramatically from none to substantial as one crossed over a threshold value well below 100 dB. In fact, even the best of the level-dependent designs only begins to provide amplitude sensitivity as sound levels equal or exceed 110 dB. Thus these types of products are only suited for protection from impulsive noises since when steady sound levels reach 110 dB the amounts of attenuation provided by such earplugs is insufficient for hearing protection.

References

[1] C. H. Allen, "Investigation of the performance and deterioration of acoustical absorbing materials under the influence of intense sound fields," BBN Report No. 792, Bolt, Beranek and Newman, Cambridge, MA, (1960)

[2] U. Ingard and H. Ising, "Acoustic nonlinearity of an orifice," *J. Acoust. Soc. Am.*, 42(1), 6-17 (1967)

[3] M. R. Forrest, "Laboratory development of an amplitude-sensitive ear plug," Royal Naval Personnel Res. Committee, Rept. HeS 133, Med. Res. Council, London, England (1969)

[4] EarPro™ by Surefire® earplug data sheet at www.earprocom.com, downloaded 2008, data referenced to the Noise Braker earplug and a study by Jack Vernon.

[5] C. H. Allen and E. H. Berger, Development of a unique passive hearing protector with level-dependent and flat attenuation characteristics," *Noise Control Eng. J.* 34(3), 97-105 (1990)

[6] P. Hamery, A. Dancer, and G. Evrard, "Study and production of nonlinear perforated earplugs (in French)," ISL R 128/97, Saint-Louis, France (1997)

[7] M. R. Forrest and R. R. A. Coles, "Use of cadaver ears in the acoustic evaluation of ear plugs," Royal Naval Personnel Res. Com., Rept. HeS 134, Med. Res. Council, London, England (1969)

[8] A. Dancer, P. Grateau, A, Cabanis, G. Barnabe, G Cagnin, T. Vaillant, and D. Lafont, "Effectiveness of earplugs in high-intensity impulse noise," *J. Acoust. Soc. Am*. 91(3), 1677-1689 (1992)

[9] J. H. Patterson Jr., B. T. Mozo, and D. L. Johnson, "Actual effectiveness of hearing protection in high level impulse noise," in *Noise & Man '93 – Proceedings of the 6th. Int. Congr., Noise as a Public Health Problem, Vo. 3*, 122-127 (1993)

[10] P. Hamery, A. Dancer, E. H. Berger, "Amplitude-sensitive attenuating earplugs," Conference/Workshop on the Effects of high intensity continuous and impulse/blast noise on humans, Moab, UT (2008)

[11] E. H. Berger, "Preferred methods for measuring hearing protector attenuation," in *Proceedings of Inter-Noise 05*, p. 58 (2005)

[12] ANSI, "Methods for measuring the real-ear attenuation of hearing protectors," Am. Natl. Stds. Inst., S12.6-1997(R2002), New York, NY (1997).

[13] G. Parmentier, A. Dancer, K. Buck, G. Kronenberger, and C Beck, "Artificial head (ATF) for evaluation of hearing protectors," *Acta Acoustica*86(5), 847-852 (2000)

[14] E. H. Berger, R. W. Kieper, and D. Gauger, "Hearing protection: surpassing the limits to attenuation imposed by the bone-conduction pathways, *J. Acoust. Soc. Am.* 114(4), 1955-1967 (2003)

[15] E. H. Berger , "Hearing protection devices," in *The Noise Manual, 5th Edition*, edited by E. H. Berger, L. H. Royster, J. D. Royster, D. P. Driscoll, and M. Layne, Am. Ind. Hyg. Assoc. , Fairfax, VA 379-454.