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Preferred Methods for Measuring Hearing Protector Attenuation

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Abstract There are numerous well-documented measurement methods available to evaluate hearing protector attenuation, however, some are flawed or difficult to implement and some can and have been misused with the erroneous results fostering misleading conclusions. This paper will examine the three most robust methods including the "gold standard" in hearing protector attenuation measurements, namely real-ear attenuation at threshold. It will be compared to the most useful alternatives such as microphone in real ear, including the use of probe microphones, imbedded microphones, and miniature microphones, and to measurements using acoustical test fixtures, also called blockheads. Examples of the latter include the ANSI- and ISO-specified blockheads, KEMAR, and others. Illustrative data will be provided to guide the user in the application of such techniques and tools, and to point out errors to avoid. None of the three methods is entirely "accurate," all being plagued by various experimental artifacts. However, REAT has been thoroughly "road tested" and standardized around the world, and has been shown to be the most accurate at estimating the performance for a defined group of subjects under a given set of conditions.

1. INTRODUCTION

Since testing hearing protector attenuation commenced approximately 50 years ago many techniques have been developed. They can be separated into subjective and objective methods, depending upon whether a listener's response or an instrument's reading is used to gauge the desired values. Berger has provided a comprehensive review to which the reader is referred for a thorough discussion (1986). He examined 13 subjective methods and an additional 4 objective methods. Since then at least two additional procedures and even more variants have been reported (Knaus and Dietz, 2004; Letowski et al., 1995). However, then as now, the most useful and accurate of these methods continues to be the subjective approach of real-ear attenuation at threshold (REAT) implemented either in a sound field or under circumaural earphones, and the two objective approaches of placing microphones in real ear (MIRE), and measuring using acoustical test fixtures (ATFs). Of these, REAT has become the gold standard, not only because it is the most conceptually straightforward and was the earliest to be codified in a national and then international standard (ANSI Z24.22; ISO 4869-1), but also because it most closely captures the performance as experienced by the user and is plagued by the fewest measurement artifacts.

Although we often speak of attenuation, with respect to acoustical measurements it is an imprecise term. The acoustical quantities that are clearly defined, which pertain to attenuation of noise, are transmission loss (TL), insertion loss (IL), and noise reduction (NR). TL refers to the difference between the incident and transmitted sound power for a partition or barrier as generally applied in architectural acoustics. The concept is not amenable to measurements of hearing protection devices (HPDs). IL is the difference between the sound pressure levels (SPLs) or any other acoustical quantity measured at a reference point before and after noise treatment. An example is sampling just inside the earcanal, with and without the HPD in place. IL is the quantity that is directly related to the effectiveness of an HPD and is analogous to the threshold shift that is measured during an REAT evaluation. NR is the difference between the incident and received SPLs, such as between and input and output of a muffler, or between the level outside and inside an HPD.

The relationship between IL and NR is shown in Figure 1 where TFOE is the transfer function of the open ear, i.e., the amplification relative to the undisturbed sound field caused by earcanal and pinna resonances. It is important to report the type of measurements that are conducted since one may directly compare IL and REAT, but if such comparisons are made using NR without a TFOE correction, 5 to 10-dB errors can result. Thus IL is a more direct measure of what we really are interested in, namely HPD effectiveness, but NR has its advantages because it can be used to measure attenuation for time-varying signals, such as gunshots, by recording from the inside and outside mics simultaneously. With IL, which requires sequential sound measurements, multiple shots are required. Since one shot is unlikely to be identical to the next, this will reduce the precision of the measurements.

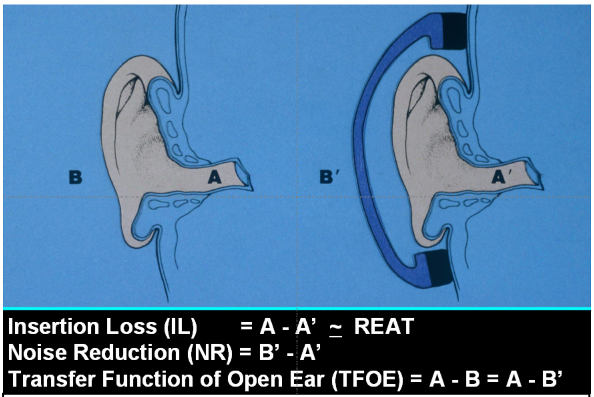

Figure 1 – Comparison of insertion loss and noise reduction. TFOE is measured with respect to point B, which is generally the head-center location with the head absent. NR = IL - TFOE.

When attenuation or noise data are reported, values are normally provided in either decibels or percent dose. I have observed published data rounded to integer values, or reported in tenths, or sometimes to 0.01 dB. What makes sense? To answer this let's examine the concept of significant figures, which is the number of figures that have meaningfulness, as estimated from the precision with which the quantity is measured. Though instruments with digital readouts often provide values to hundredths of a dB or hundreths of a percent, this is misleading and can be confusing. For example, most would agree that when measuring decibels, when one accounts for microphone tolerances, sampling errors, and actual variation in the quantity itself, a precision of 0.1 dB or better may be possible in a calibration laboratory, but not elsewhere. In typical psychoacoustic measurements achieving ±0.5 dB is possible, though in threshold determinations (as used in REAT) one does well to meet ±1.0 dB, but usually ±2.0 dB or greater. In field sampling of noise exposures ±2.5 dB is good if it can be achieved. Thus it makes no sense to report values to 0.01 dB. In many cases rounding to integer values is apropos unless subsequent computations will be conducted using the data, in which case an extra digit may be carried to avoid rounding errors.

With respect to measured values of noise dose, Table 1 provides data to guide in the determination of meaningfulness. The table indicates the computed doses for continuous 8-hr. exposures to various sound levels. Note how small changes in the SPL gives rise to changes in the computed dose of from 1% to 21%. Considering that measurements in dB are rarely made with a precision of 1 dB (as discussed above), it is clear that reporting measured dosimeter values to tenths or hundredths of a percent is meaningless and misleading.

A final prefatory remark pertains to the estimation of the performance of HPDs in real-world situations. Much has been written on this topic, however, that is beyond the focus of this review. Suffice it to say that certain implementations of the REAT procedure (see Method B of ANSI S12.6-1997 and SA/SNZ 1270) that particularly strive to more closely approximate usage conditions can provide closer estimates of field performance (Berger et al., 1998; Gauger and Berger, 2004). Unbiased real-world estimates become more difficult to achieve as experimenter involvement with the subjects increases, as can happen with MIRE measurements, or as the subjects are removed altogether as in the case of ATF measurements.

Table 1 - Example of effect of small changes in the steady-state SPLs on the computed dose in %, for 8-hr. exposures. Effects are greater at higher doses.

SPL (dB)	Δ dB	Computed Dose %	Δ Dose %
85.0	-	50	-
85.1	0.1	51	1
86.0	1.0	57	7
87.5	2.5	71	21
90.0	-	100	-
90.1	0.1	101	1
91.0	1.0	115	15
92.5	2.5	141	41
100.0	-	400	-
100.1	0.1	406	6
101.0	1.0	459	59
102.5	2.5	566	166

2. REAL-EAR ATTENUATION AT THRESHOLD

REAT is a straightforward measurement of the shift in thresholds between occluded and unoccluded conditions for a group of subjects. Defining how the subjects will be selected, trained, coached, and fitted with the HPDs is by far the dominant factor influencing the results; controlling the background noise in the test environment and the distortion in the test signals are the most critical technical aspects of the procedure. REAT conducted in a sound field is the "gold standard" worldwide and the one with the most extensive history. American National Standards Institute documents pertaining to REAT first appeared in 1957, and then again in 1974, 1984, and 1997 (ANSI Z24.22, S3.19-1974, S12.6-1984, S12.6-1997 and reaffirmed in 2002). International standards first appeared in 1981 and again in 1990 (ISO 4869:1981, 4869-1:1990). Equivalent standards have been promulgated in other countries as well (BS 5108:1983; JIS T 8161-1983; SA/NZS 1270:2002; IS 6229-1971). REAT can also be conducted under circumaural headphones (Berger, 1986 and 1989) as long as suitable correction factors are included to adjust the values to match the sound-field data. With this REAT implementation, of course, measurements are only possible on insert HPDs.

REAT accounts for all the relevant sound paths to the protected ears, including the bone-conduction pathways, and the values provide a valid indication of the protection provided for the subjects utilized and for the way in which the HPDs were fitted for the test. The method has been shown to be predictive of attenuation over a wide range of sound levels, even though the measurements themselves are conducted within 50 to 60 dB of the threshold of hearing. REAT will generally underestimate protection for intentionally level-dependent

HPDs that are designed either by passive or electronic means to increase protection as sound level increases (Berger, 1986). The one known artifact of the procedure is that physiological noise in the protected condition is sufficiently amplified by the occlusion effect to mask the thresholds and thus spuriously increase the difference between the open and protected thresholds, and hence the measured attenuation. This effect is limited to frequencies below about 500 Hz and to magnitudes of up to about 6 dB (Berger and Kerivan, 1983; Gauger, 2003).

3. MICROPHONE IN REAL EAR (MIRE)

MIRE is a direct analog of REAT, but the sensor in this case is a suitably positioned microphone instead of the eardrum/cochlea. The key in this procedure is how to place a microphone in the earcanal or in the HPD in a way so as not to materially affect the performance of the hearing protector, and in the case of measurements intended to capture real-world performance, not affect the performance of the person fitting the device either.

Besides the issue of affecting the fit of the HPD, the principal concern to contend with is that MIRE does not capture all of the sound pathways to the ear in the same way as does REAT. The missing pathways are the bone-conduction pathways that circumvent the HPD. For real ears, the response to an incoming sound wave may be through vibration of the eardrum or by direct excitation of the cochlea via sound that stimulates the bone- and tissue-conduction pathways. In the MIRE procedure, essentially the only path of excitation is down the earcanal, unless the mic is unusually susceptible to vibratory excitation and in that case its sensitivity would be highly unlikely to mimic the real-ear and the data would still be contaminated. This lack of bone-conduction stimulation in MIRE tends to cause the results to be spuriously high above 1 kHz, since in that frequency range the attenuation of an HPD in real ears can often be great enough to be influenced (i.e., limited) by bone-conduction transmission.

One advantage of MIRE is that it can be used to test attenuation over a wide range of sound levels in order to explore the potential level-dependent attenuation of certain devices. However, when implemented in an IL paradigm, this requires the open-ear condition to be unprotected. For high-level sounds this can be problematic and limits the levels that can be tested. Alternatives are to implement MIRE using an NR paradigm (i.e., microphones inside and outside the HPD), in which case the ear is always protected, or to utilize the approach taken in the ANSI MIRE standard (S12.42-1995). In that case the mic in the earcanal is affixed to the surface of a foam or premolded earplug that is present in the ear for both protected and unprotected measures on an earmuff. The microphones can be positioned in the earcanal (using hearing-aid sized mics or probe tubes), or at the entrance of the canal, or can penetrate or be part of the hearing protector. Figure 2 depicts a probe mic and miniature mic as compared to the size of an earplug. Figure 3 depicts a mic (in plastic case) that can be screwed into the back of a foam earplug. This type of mounting has been successfully used

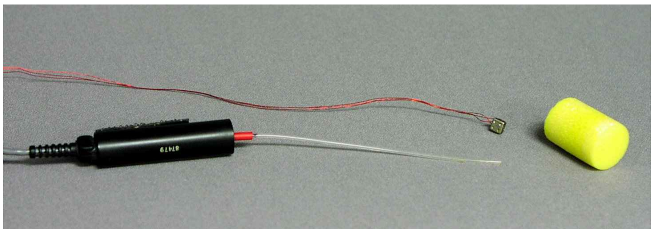

Figure 2 – Example of a hearing-aid sized microphone with fine AWG 64 wire, and a probe microphone with attached flexible silicone tubing.

for day-long monitoring of protected exposure levels of employees in noisy occupations (Burks and Michael, 2003)

Figure 3 – Microphone mounted in plastic case for attachment to lateral end of earplug.

When using a probe, care must be exercised to avoid or at least to recognize and correct for a flanking pathway that can occur when sound enters the exposed portion of the probe tube (between the probe body and the tube's penetration through the earplug) and is then picked up by the mic as though it had penetrated the earplug and entered the open end of the tube that looks into the earcanal. This flanking pathway will increase the measured sound levels and reduce the estimated attenuation. Figure 4 depicts another possible error when a probe is passed between the earplug surface and the canal walls. A leak can occur that can dramatically reduce protection.

Figure 4 – Note the leak at 5 o'clock where the probe tube passes between the plug's flange and the canal wall.

Figure 5 presents data from one carefully controlled set of MIRE measurements on earmuffs. It illustrates the types of differences to be expected when REAT and MIRE data are exactingly measured and compared on one group of test subjects, utilizing the same fitting of the devices for both test methods. Note that at 125 Hz the REAT values are high due to physiological noise masking, but from 500 to 6300 Hz the MIRE values are high, most likely because they do not account for the flanking bone-conduction pathways. It is interesting to note that the standard deviations are only marginally less for the MIRE procedure, an observation also noted some years earlier by Berger and Kerivan (1983).

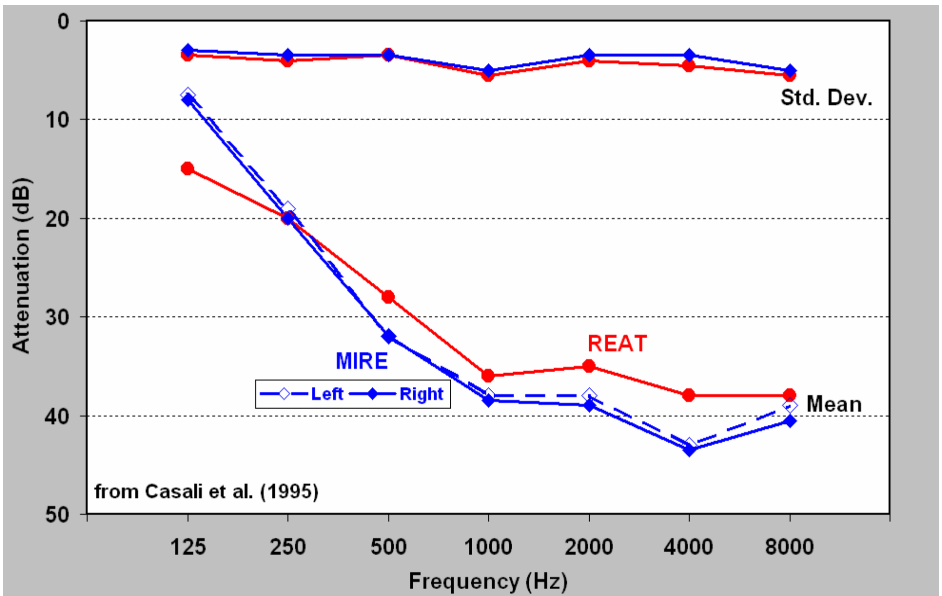

Figure 5 – Comparison of REAT to left- and right-ear MIRE data averaged across three earmuffs.

4. ACOUSTICAL TEST FIXTURES (ATFS)

If only ATFs could be used for HPD testing it would surely simplify the life of the experimenter – no pesky subjects to deal with and perhaps more repeatable results, and quicker too! Unfortunate as it may be, using ATFs is sometimes, as they say, tantamount to throwing the baby out with the bathwater. Although subjects do prolong the testing and may increase variability, they are vital for two reasons. No ATF yet designed can properly simulate all the features of the human head and auditory system, and more important, it is exactly the human involvement – the ergonomics, the fit, and the comfort, that so strongly influence HPD performance that should be captured as much as possible in the testing scenario. Nevertheless, well-designed ATFs can facilitate measurements, perform well for quality control, and allow data acquisition under conditions that would otherwise be unsuitable for human subjects without great difficulty. Such conditions include evaluation of HPD attenuation for high-level impulses from blasts, gunshots, and heavy military weapons (Parmentier et al., 2000). Testing with ATFs usually follows an IL paradigm with measurements being taken with and without the HPD in place.

Perhaps the best known and oldest of the ATFs, also called manikins, in use today is KEMAR (Burkhard and Sachs, 1975), the most thoroughly researched is the one developed by Schroeter et al. (Schroeter and Els, 1982; Schroeter and Poesselt, 1986), and the most standardized are the simple metal blockheads called for by ANSI and ISO that are utilized primarily for quality assurance testing (ANSI S12.42-1995; ISO/TR 4869-3). Arguably the most unusual ATFs are KOJAK with adjustable head width and hair pieces (Russell and May, 1976), and the head developed by May and Dietz (2004) that was constructed from a human skull stuffed with silicone-filled balloons to simulate and allow measurement of the bone-conduction pathways.

To act as a proper surrogate, an ATF should:

- match the dimensions of human heads and earcanals, and depending on the application also include an accurate pinna simulation,
- mimic not only the geometry but also the mechanical characteristics of the pinna for devices that rest upon the ear such as supra-aural HPDs,
- match human eardrum impedance when the ATF will be used for earplug measurements,
- include a skin simulation around the ear for earmuffs, and in the canal for earplugs,
- match the frictional coefficient, and perhaps the textural characteristics as well, of the earcanal flesh, for testing earplugs,
- include effects of the bone-conduction pathways via mechanical simulation, or possess sufficient self-insertion loss so that flanking mechanical pathways are nil and can be included via post-measurement mathematical correction,
- account for the occlusion effect and physiological-noise masking (usually done as post-measurement correction),
- and perhaps allow for a variety of shapes of heads and earcanals if the intent is to see how devices can fit different users.

No ATF has fulfilled all of these requirements, though many researchers have made concerted efforts to create one that does. Whatever device is selected, the user should be well aware of its limitations and the fact that it will be unable to reproduce the human factors and behavioral aspects in their entirety.

Knowles Electronic Manikin for Acoustic Research (KEMAR), mentioned above, was primarily designed for hearing-aid research and engineering. However, a number of authors have utilized KEMAR for HPD measurements, sometimes overlooking its limitations and drawing inappropriate conclusions. Berger (1992) has discussed these issues illustrating the correct use vs. misuse of KEMAR for such measurements. Figure 6 illustrates KEMAR and its earcanal. Limitations of KEMAR to measure conventional passive earmuffs and earplugs include inadequate self-insertion loss, seams/discontinuities around the base of its pinna, and a lack of both circumaural and earcanal flesh simulations.

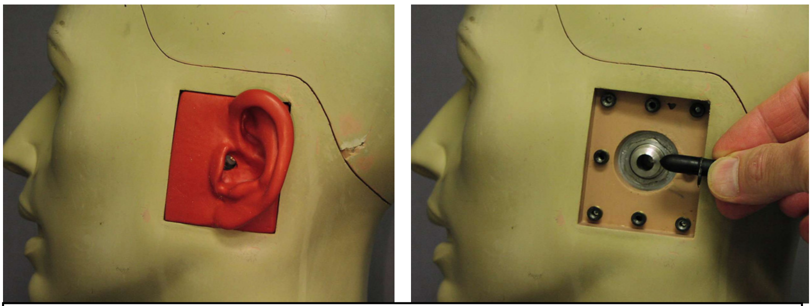

Figure 6 – KEMAR with pinna simulation on left, and on right with pinna removed exposing cylindrical metal earcanal in comparison to a flangeless earplug.

Figure 7 depicts, the Bruel & Kjaer 4128 head and torso (HATS) simulator, one of the newer ATFs specifically designed to incorporate features intended to permit measurement of hearing protector attenuation. Nevertheless, its results for earplugs do not completely reproduce REAT values and its method of pinna installation still results in a discontinuity around the ear that is problematic for testing circumaural devices. Wargowske et al. (1995) evaluated both the 4128 and the Head Acoustics HMS II using a number of earplugs. Their data, depicted in Figures 8 and 9 for a foam earplug, represent the range of values they observed using various insertion depths and post-measurement correction factors on both heads. Similar results were found for other plugs.

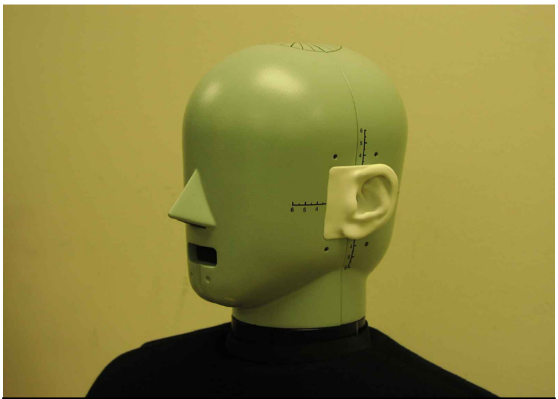

Figure 7 – B&K 4128 Head and Torso Simulator

Figure 8 shows that the uncorrected curves provide a poor approximation of REAT. The values at 125 Hz are low relative to REAT, which as previously mentioned is known to yield spuriously high data at low frequencies. At other frequencies, for example above 500 Hz, the HMS data are wildly high (greater than 60 dB) and need correction by factoring in the bone-conduction pathways. The corrected data for both ATFs, mathematically manipulated for the occlusion effect and physiological-noise masking, are a better approximation of REAT, but still not as close as desirable.

In Figure 9 data are presented for a different fit of the earplugs in the ATFs; the experimenters purposely tried to match the REAT data arguing that just as earplug fit can affect results on real heads, it does so on ATFs, and they needed to have similar insertions in both cases. Data are also shown in Figure 9 for alternate post-measurement corrections based on different empirical data and theory. The results are closer to REAT values, and in fact if the data from the two heads are averaged, treating them as though they are an "ATF panel" comparable to a listener panel of real subjects, the results are closer still.

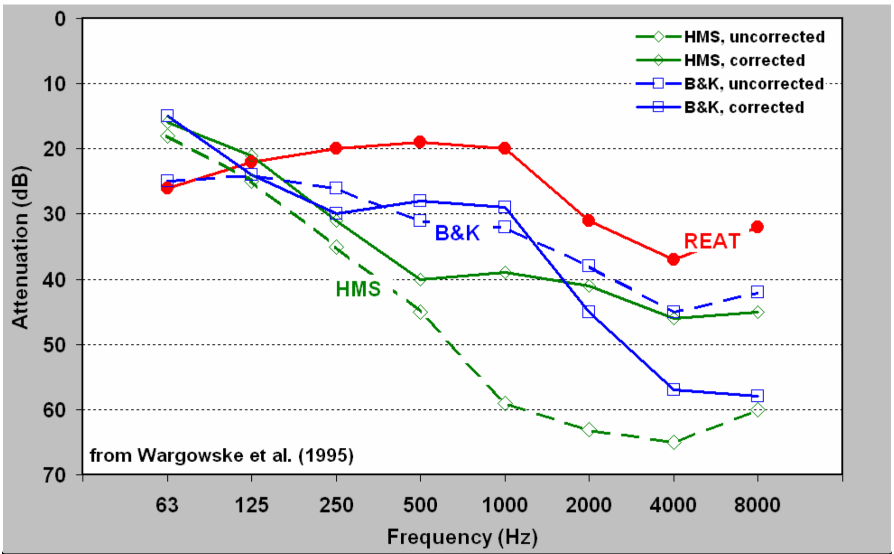

Figure 8 - Comparison of REAT to uncorrected- vs. corrected-IL, for a foam earplug measured on two commercially available ATFs.

The point to be gleaned here is that use of ATFs is not straightforward and requires experimentation and calibration if the intention is to make accurate predictions of absolute values of attenuation. Even with the best ATFs one can never be certain that the performance for any one HPD will be estimated correctly. Normally for earmuffs the estimates are more reliable. Regardless of the degree of development of ATFs over the coming years, it is likely that post-measurement corrections will still be required. Furthermore, trying to capture some estimates of the human factors issues and real-world performance will remain a difficult endeavor.

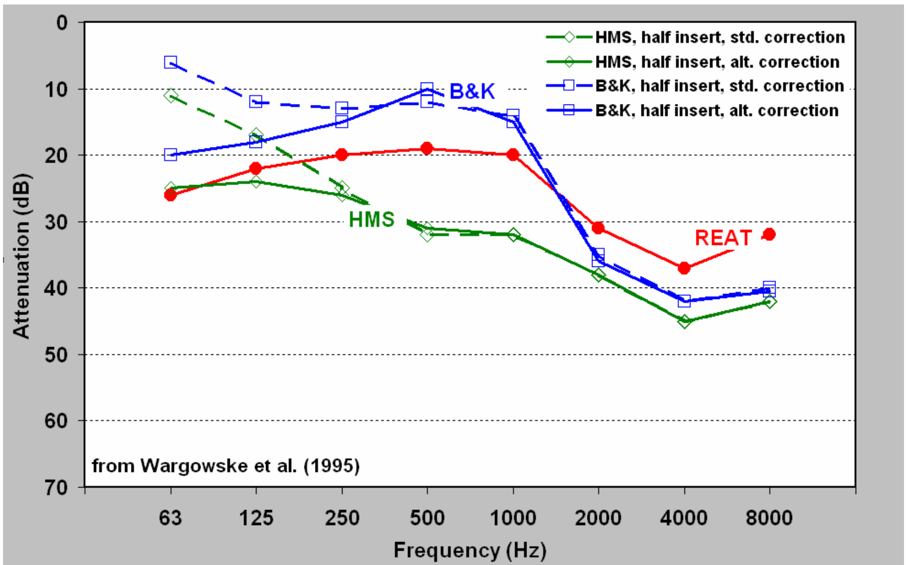

Figure 9 - Comparison of REAT to corrected-IL (two different methods, see text) for a foam earplug with shallower fit than used in Fig. 8, measured on two commercially available ATFs.

5. CONCLUSIONS

Three methodologies for the measurement of the attenuation of hearing protectors have been briefly reviewed. They include a purely subjective procedure, REAT, and two objective procedures. In the latter case one of the procedures, MIRE, still incorporates the use of human subjects, whereas the other is completely objective, relying only on the use of ATFs. The advantages of the human-subject based procedures is that they can better simulate the varied aspects of HPD performance on real heads, whereas the ATF approach better lends itself to automation and to testing with acoustical stimuli to which it is either impossible or too dangerous to expose human subjects. Both of the objective methods are preferred when HPD performance for acoustical stimuli over a range of sound levels and at levels above threshold need to be assessed. This is usually the case with intentionally level-dependent HPDs, with devices that include transducers and other electronics, and when performance measures are required for situations in which users are exposed to high-level impulses as is often the case when firing military weapons systems.

None of the three methods is entirely “accurate,” all being plagued by various experimental artifacts. However, REAT has been thoroughly “road tested” and standardized around the world, and has been shown to be the most accurate at estimating the performance for a defined group of subjects under a given set of conditions. One might argue that since REAT is known to provide high estimates of attenuation at and below 250 Hz that the results should be corrected for this error. The difficulty is that the error is dependent upon both the fit of the device being tested and its physical characteristics, and thus far there has been no successful approach to develop a valid “one-size-fits-all” correction. Any such adjustments would also cause serious confusion for manufacturers and users alike, with respect to the half-century of uncorrected REAT data that have been published and utilized.

With respect to MIRE and ATF data, corrections of a larger magnitude (than with REAT) are required, but again the variability between HPDs and even test laboratories is such that the corrections must be devised on an ad hoc basis. Whatever method is employed the experimenter is encouraged to become fully knowledgeable with the myriad details and idiosyncrasies of the procedure and its applicability to the task at hand.

6. REFERENCES

[1] ANSI (1957). "Method for the Measurement of Real-Ear Attenuation of Ear Protectors at Threshold," American National Standards Institute, Z24.22-1957 (R1971), New York, NY.

[2] ANSI (1974). "Method for the Measurement of Real-Ear Protection of Hearing Protectors and Physical Attenuation of Earmuffs," American National Standards Institute, S3.19-1974 (ASA STD 1-1975), New York, NY.

[3] ANSI (1984). "Method for the Measurement of the Real-Ear Attenuation of Hearing Protectors," American National Standards Institute, S12.6-1984, New York, NY.

[4] ANSI (1995). "Microphone-in-Real-Ear and Acoustic Test Fixture Methods for the Measurement of Insertion Loss of Circumaural Hearing Protection Devices," American National Standards Institute, S12.42-1995, New York, NY.

[5] ANSI (1997). "Methods for Measuring the Real-Ear Attenuation of Hearing Protectors," American National Standards Institute, S12.6-1997 (R2002), New York, NY.

[6] Berger, E. H. (1986). "Review and Tutorial - Methods of Measuring the Attenuation of Hearing Protection Devices," J. Acoust. Soc. Am. 79(6), 1655-1687.

[7] Berger, E. H. (1989). "Exploring Procedures for Field Testing the Fit of Earplugs," in Proceedings, 1989 Industrial Hearing Conservation Conference, Off. Eng. Serv., Univ. Kentucky, Lexington, KY, 7-10.

[8] Berger, E. H. (1992). "Using KEMAR to Measure Hearing Protector Attenuation: When it Works, and When it Doesn't," in Proceedings of Inter-Noise 92, edited by G. A. Daigle and M. R. Stinson, Noise Control Foundation, Poughkeepsie, NY, 273-278.

[9] Berger, E. H., Franks, J. R., Behar, A., Casali, J. G., Dixon-Ernst, C., Kieper, R. W., Merry, C. J., Mozo, B. T., Nixon, C. W., Ohlin, D., Royster, J. D., and Royster, L. H. (1998). "Development of a New Standard Laboratory Protocol for Estimating the Field Attenuation of Hearing Protection Devices. Part III. The Validity of Using Subject-Fit Data," J. Acoust. Soc. Am. 103(2), 665-672.

[10] Berger, E. H. and Kerivan, J. E. (1983). "Influence of Physiological Noise and the Occlusion Effect on the Measurement of Real-Ear Attenuation at Threshold," J. Acoust. Soc. Am. 74(1), 81-94.

[11] BSI (1983). "Measurement of Sound Attenuation of Hearing Protectors," British Standards Institution, BS 5108:1983, London, England.

[12] Burkhard, M. D. and Sachs, R. M. (1975). "Anthropometric Manikin for Acoustic Research," J. Acoust. Soc. Am. 58(1), 214-222.

[13] Burks, J. A. and Michael, K. L. (2003). "A New Best Practice for Hearing Conservation: The Exposure Smart Protector (ESP)," in Proceedings of Noise-Con 2003, edited by D. K. Holger and G. C. Maling, Jr., Inst. Noise Control Eng. USA, Washington, DC, paper 009.

[14] Casali, J. G., Mauney, D. W., and Burks, J. A. (1995). "Physical versus Psychophysical Measurement of Hearing Protector Attenuation - a.k.a. MIRE vs. REAT," Sound and Vibration 29(7), 20-27.

[15] Gauger, D. (2003). "Testing and Rating of ANR Headsets," U. S. EPA Workshop on Hearing Protector Devices, Washington, DC.

[16] Gauger, D. and Berger, E. H. (2004). "A New Hearing Protector Rating: The Noise Reduction Statistic for Use with A Weighting (NRS_A)," report prepared at the request of the U. S. EPA, reviewed and approved by ANSI S12/WG11, E•A•R 04-10/HP, Indianapolis, IN.

[17] IS (1971). "Method of Measurement of Real-Ear Attenuation of Ear Protectors at Threshold," Indian Standard, IS:6229-1971, New Delhi, India.

[18] ISO (1981). "Acoustics - Measurement of Sound Attenuation of Hearing Protectors - Subjective Method," International Organization for Standardization, ISO 4869, Switzerland.

[19] ISO (1990). "Acoustics - Hearing Protectors - Part 1: Subjective Method for the Measurement of Sound Attenuation," International Organization for Standardization, ISO 4869-1:1990(E), Switzerland.

[20] ISO (1989). "Acoustics - Hearing Protectors - Part 3: Simplified Method for the Insertion Loss of Earmuff Type Hearing Protectors for Quality Inspection Purposes," International Organization for Standardization, ISO 4869-1:1989(E), Switzerland.

[21] JSA (1983). "Ear Protectors," Japanese Industrial Standard, JIS T 8161-1983, Tokyo, Japan.

[22] Knaus, D. A. and Dietz, A. J. (2004). "An Objective Method for Measuring the Attenuation of Hearing Protection Devices Using Otoacoustic Emissions," J. Acoust. Soc. Am. 116 (4), Pt. 2, p. 2596.

[23] Letowski, T., Burstein, N., Clark, J., Romanowski, L., and Sevec, A. (1995). "Most Comfortable Loudness Shift as a Measure of Speech Attenuation by Hearing Protectors," Am. Ind. Hyg. Assoc. J. 56(4), 356-361.

[24] May, B. S. and Dietz, A. J. (2004). "Skull Simulator for Design of Hearing Protection Systems for Bone-Conducted Sound," J. Acoust. Soc. Am. 116 (4), Pt. 2, p. 2625.

[25] Parmentier, G., Dancer, A., Buck, K., Kronenberger, G., and Beck, C. (2000). "Artificial Head (ATF) for Evaluation of Hearing Protectors," Acta Acustica 86(5), 847-852.

[26] Russell, M. F. and May, S. P. (1976). "Objective Test for Earmuffs," J. Sound Vib. 44(4), 545-562.

[27] SA/SNZ (2002). "Acoustics - Hearing Protectors," Standards Australia and Standards New Zealand, 1270:2002, Sydney, NSW.

[28] Schroeter, J. and Els, H. (1982). "On Basic Research Towards an Improved Artificial Head for the Measurement of Hearing Protectors," Acustica 50(4), 250-260, and 51(6), 302.

[29] Schroeter, J. and Poesselt, C. (1986). "The Use of Acoustical Test Fixtures for the Measurement of Hearing Protector Attenuation. Part II: Modeling the External Ear, Simulating Bone Conduction, and Comparing Test Fixture and Real-Ear Data," J. Acoust. Soc. Am. 80(2), 505-527.

[30] Wargowske, J., Fedtke, T., and Richter, U. (1995). "Insertion Loss of Ear-Plugs, Measured on New Versions of Two Commercially Available Head and Torso Simulators," PTB-Bericht, PTB-MA-43, Braunschweig, Germany.