Alternative Field Methods for Measuring Hearing Protector Performance

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In comparison with the mandatory noise reduction rating (NRR) testing of every hearing protector sold in the United States, real-world tests of hearing protector attenuation are scarce. This study evaluated data from three potential field-test methods as compared with the subject-fit data from Method B of ANSI S12.6–1997 for the E•A•R® Express™ Pod Plug™. The new field-test methods were the FitCheck headphone (FCH) method, FitCheck in sound field (FCSF) method, and bone-conduction loudness balance (BCLB) method, all of which can be administered in small single-person audiometric booths such as are commonly found in industry. Twenty normal-hearing and audiometrically competent subjects naive to hearing protector use were tested with the laboratory and the three field-test methods in a repeated-measures design. Repeated-measures models with structured covariance matrices were used to analyze the data. Significant effects were found for method, frequency, and first-order frequency-by-gender and frequency-by-method interactions. These effects and interactions were expected given the different psychophysical tasks. The FCSF and BCLB methods provided attenuations that were not significantly different from those found with Method B. Although the attenuations measured for the FCH method were statistically different (greater) than the attenuations from the other methods, the differences were within the magnitude of acceptable test-retest audiometric variability. The results suggest that the FCH and FCSF methods were both feasible and reliable methods for field testing. The FCH method is limited to testing earplugs, and the FCSF requires additional equipment to outfit the test booth, but could be used for testing all types of protectors.

Keywords: attenuation, hearing, hearing protectors, noise, real-ear-attenuation-at-threshold (REAT)

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The American Standards Association method ASA Z24.22 for measuring hearing protector device (HPD) attenuation,[1] issued in 1957, required the subject to be seated in an anechoic sound field directly in front of a loudspeaker while performing pure-tone free-field audiometry with and without the HPD. The difference between the hearing threshold levels with the HPD (occluded) and without the HPD (open) was the real-ear-attenuation-at-threshold (REAT) for the protector at that test frequency. REATs varied as much as 15 dB for a given frequency, dependent on the angle of sound incidence. In addition, because resonances in the protector and ear canal volume were frequency specific, pure-tone REATs reflected only the attenuation at the test frequencies.

ASA Z24.22 was replaced by the ANSI S3.19–1974[2] standard that specified third-octave narrow-band noise stimuli, presented in a uniform, nondirectional, reverberant sound field. ANSI S3.19 specified the diffusivity of the sound field within the critical volume in which the subject's head would be located during the test. A diffuse sound field was defined as uniform in a volume of 0.10 m front to back and of 0.15 m side to side and top to bottom, such that the range of sound levels was within 6 dB for all test bands for the front-back and top-bottom reference positions and within 2 dB for the side-to-side positions. Furthermore, ANSI S3.19 specified the minimum and maximum reverberation times of the sound field measured at the center of the critical volume. ANSI S3.19 described two methods to fit protectors under test conditions, experimenter-fit (EF) and subject-fit (SF), but neither was clearly defined. The ANSI S3.19–1974 EF procedure was intended to ensure greater consistency in the fitting of the protectors during testing, especially across laboratories. In 1978 the U.S. Environmental Protection Agency (EPA) required that the EF method[3] be used when protectors were tested for labeling purposes. The EPA interpreted the EF method to mean that the subject played no role in the insertion of earplugs or ear canal caps or the placement of earmuffs.

In the middle to late 1970s continued studies of field-measured or real-world REATs of HPDs found substantially lower values than were predicted by ANSI S3.19–1974.[2] By 1982 ten studies measuring real-world REATs had collected data from 50 North American industries.[4] The results demonstrated that the EF laboratory data collected by ANSI S3.19–1974 consistently overpredicted real-world attenuation, and that it was not possible to predict the real-world REATs from the laboratory EF REATs for any given protector or class of protectors.

Discrepancies between real-world and EF data led to the development of the experimenter-supervised fit protocol in ANSI S12.6–1984.[5] The experimenter-supervised fit was designed to optimize the REATs of informed and motivated users. The experimenter and test subjects were to work together to achieve the best fit of a protector before each occluded test, including using fitting noise to assure that both ears were equally well fit. ANSI S12.6 also allowed for the creation of a diffuse sound field in an anechoic or acoustically treated space by removing the minimum reverberation times for the sound field. ANSI S12.6–1984 was intended to replace the older standard, but ANSI S3.19 was not officially rescinded by ANSI until 1997. In the absence of any activity by the EPA, the ANSI S3.19 standard has continued as the basis of federal regulation 40 CFR part 211. Thus, manufacturers have had no incentive to retest their products according to ANSI S12.6–1984 or its successor, ANSI S12.6–1997.

A subsequent review of 22 real-world studies that tested protectors with both REAT and microphone-in-real-ear (MIRE) protocols found that the EF data from the ANSI S3.19 standard were inconsistent regardless of type of protector.[6] As a result, the National Institute for Occupational Safety and Health (NIOSH) recommended that the noise reduction ratings (NRRs) calculated from ANSI S3.19 REATs be derated by 25% for earmuffs, by 50% for slow-recovery foam earplugs, and by 70% for all other earplugs.[7] OSHA requires its inspectors to derate all HPDs by 50% before calculations are done to determine whether the HPD's protection is an adequate substitution for noise control.[8] A recent study by NIOSH confirmed that, across the board, derating schemes such as OSHA's and NIOSH's do not predict SF data.[9] Thus, although derating schemes reduce the NRRs, the lowered ratings are not representative of real-world REAT data for the same devices.[10]

In response to the overestimation of real-world protection by the NRR, the ANSI standards working group S12/WG11 was chartered to develop a more predictive laboratory method and to develop methods that could be used to measure REATs for workers as they wear their HPDs. Deciding to tackle the issue of a more predictive laboratory method first, the working group guided 10 years of interlaboratory studies on various test methods, including the SF procedure. This method was originally incorporated in ANSI S3.19–1974, revised in ANSI S12.6–1984 (experimenter-supervised fit), and then modified further to remove all experimenter involvement in the fitting of HPDs. The interlaboratory studies coordinated by the working group found that SF REATs had less variability across laboratories than the experimenter-assisted methods[11] and were predictive of real-world REATs, thus bringing laboratory REATs in line with real-world REATs. As a result of the research the SF method was incorporated in ANSI S12.6–1997 as Method B.[12] Method B has a highly structured format, including instructions to subjects that are read verbatim by experimenters.

Throughout the revisions of the methods for evaluating hearing protection devices, the procedure for determining attenuation remained the same, subtraction of ears-open from ears-occluded hearing threshold level to calculate the REAT. The REAT method was the most common metric in the real-world studies summarized by Berger et al. (1996).[6] One alternative to the REAT method is the bone-conduction loudness-balance (BCLB) method reported by Rimmer and Ellenbecker.[13] This procedure utilizes pulsed third-octave noise-band sounds delivered alternately by a bone-conduction vibrator on the forehead of the subject and by a loudspeaker in a sound field. The bone-conduction sound level is the referent, remaining at a fixed level, while the subject, to bracket the point of equal loudness between bone-conducted and air-conducted sound pulses, varies the level of the air-conducted signal. The difference between the sound pressure level of air-conducted signals at equal loudness for the unoccluded and occluded conditions should be equivalent to the REAT for an HPD. To circumvent the occlusion effect on bone-conducted signals, Rimmer and Ellenbecker[13] employed a bifrequency loudness balance, keeping the bone-conducted noise band centered at 2000 Hz where occlusion effect is negligible. Rimmer and Ellenbecker reported good agreement between their BCLB attenuations and the labeled REATs for the HPDs they tested.

Michael & Associates (State College, Pa.) recently introduced the FitCheck system[14] for measuring REATs on individuals. FitCheck is a computer-controlled version of a system originally developed in the 1970s by NIOSH.[15] To create the test space, the FitCheck system employs large circumaural earcups, each with a pair of small loudspeaker elements. As such, the FitCheck system may be used only for earplugs. However, independent determination of the REAT for each ear is possible, unlike the sound-field laboratory and BCLB procedures, which are binaural tests.

This article compares the SF test results for alternative fit-test systems with the SF (Method B) laboratory method of ANSI S12.6–1997. Because the Method B SF data have been shown to be predictive of real-world outcomes,[10] it was selected over the EF method, which would introduce an experimenter effect.[9] The results may guide the selection of one of the methods, BCLB or FitCheck, for future deployment in work-site intervention studies.

METHODS AND MATERIALS

One hearing protector was chosen for this study, the E•A•R® Express™ Pod Plug™. This earplug proved to yield consistent fitting; that is, no subject inserted it sideways or backward. The earplug's stem aided the subject in orienting the plug for insertion into the ear canal. The Express plug also has a foam hemispherical flange that allows it to conform to the ear canal shape.

Equipment

Diffuse Sound-Field Testing (ANSI S12.6 Method B)

Subject-fit REATs were measured at the NIOSH Hearing Protector Laboratory inside a Tracoustics RE-245 double-walled, double-floored test booth modified to be a reverberant chamber according to ANSI S12.6–1997 Method B. The diffuse sound-field

(DSF) environment was produced by three loudspeaker arrays placed orthogonally in the chamber (facing front to back, left to right, and down to up). Each loudspeaker array was composed of a 15-inch woofer, a midrange horn, and a high-frequency horn tweeter. The critical volume had a radius of 0.15 m in the center of the room where sound levels varied less than 2 dB at the left and right, front and back, and top and bottom points of measurement. The subjects could sit comfortably and keep their heads inside the critical volume without reliance on head-placement instruments such as plumb bobs and headrests to mark space-boundaries.[16]

Test signals consisted of third-octave narrow-bands noise with center frequencies at 125, 250, 500, 1000, 2000, 3150, 4000, 6300, and 8000 Hz. The frequency bands 3150 and 6300 were included to allow comparison with tests of other protectors that were tested in those bands. Noise bursts were 200 msec in duration, had a 10 msec rise-fall time, had a 50% duty cycle, and were presented in groups of three. All tasks of noise-band selection, gating, attenuation, recording of listener responses, calculation of thresholds, and recording of results were performed by a custom developed computer hardware and software system called Automated Sound-Field Threshold Testing system.[16] Hearing threshold levels were determined to the nearest decibel using a modified Hughson-Westlake method.[17]

Bone-Conducted Loudness Balance Testing

Tests performed according to the BCLB method[13] were also obtained in the same diffuse sound-field environment, except that a Grason-Stadler GSI-10 audiometer controlled the presentation of signals. Each third-octave noise band with a center frequency of 250, 500, 1000, 2000, 3150, 4000, or 6300 Hz was delivered to the external input of the audiometer. Due to limits of the bone vibrator the test frequencies were restricted to the 250–6000 Hz range. The audiometer was set to pulse with duration of 200 msec and 50% duty cycle and alternated between sound-field and bone-conducted presentations. The bone-conducted signal was delivered to a Radioear B-72 vibrator placed on the forehead of the listener. The sound-field signal was delivered to the power amplifier and loudspeaker array as described above. This configuration produced a signal that appeared to go back and forth from inside a listener's head to the diffuse sound field. The subject's task was to match the loudness of the noise band delivered by the Radioear vibrator with the air-conducted stimulus. The center frequency of the bone- and air-conducted noise bands were the same. The level of the bone-conducted signal was maintained at 40 dB HL re ANSI S3.6–1996[18] for each test noise band.

The audiometer was set to a self-recording mode at an attenuation rate of 5 dB/sec with the subject controlling the level of the sound-field signal. The subject was instructed to press the response button when the signal in the sound field was louder than the signal in his or her head and to release the button when the signal was softer. Each test noise band was presented for 60 sec. Traces were obtained on an X-Y recorder. An average of the midpoints of at least six pen excursions was recorded as the point of equal loudness.

FitCheck Headphone and FitCheck Sound-Field Testing

The FitCheck headphone method (FCH) and a FitCheck in sound-field method (FCSF) were both conducted in a conventional small audiometric test booth (IAC model 401). The FitCheck software was installed on a Dell 450SL computer running Windows® 95 equipped with a Turtle Beach Monterey 32-bit sound card. The sound card played three noise bursts from WAV files to the FitCheck recording attenuator that connected to either the FitCheck headphones or the sound-field speaker system.

During the test the subject depressed the response switch until the stimulus was inaudible. Once the stimulus was inaudible, the subject released the switch, and the stimulus' loudness increased. The Bekesy test paradigm used a rate of 3 dB/sec and rejected thresholds if any of the maximums were less than any minimums and excursions greater than 20 dB. Headphone signals were delivered binaurally to simulate sound-field testing. The thresholds were the average of the minimums and maximums and ignored the first reversal. If the reversals were inconsistent, the software automatically initiated a second test of that frequency. If the second test failed, the software progressed to the next frequency in the sequence and did not record a response for the failed test frequency. In an industrial setting the hearing conservationist could use the FitCheck software to build a report of the personal attenuation rating for a subject that would be calculated from the test in a manner similar to the NRR.

Hearing threshold levels for occluded and unoccluded conditions were stored in a Microsoft Access™ database and analyzed off-line. The FitCheck database had two tables that recorded all information related to a subject's test. The first table contained the raw attenuations for the trials, a flag for occluded and unoccluded conditions, and other information about the subject and protector. The second table contained the calculated attenuations used in the personal attenuation rating. In this article the raw attenuations were used to calculate the REATs and compare with the other methods.

When the FCSF method was used, the signal from the FitCheck recording attenuator was delivered to a Stewart M-1 preamplifier and a Stewart PA-1400 power amplifier, respectively. The power amplifier drove three Bose B25 loudspeakers positioned at the subjects' eye level. The subjects were seated such that two speakers were in front of them (±45°) and one speaker was directly behind them (180°). Because the FitCheck system was designed to drive headphones with a monaural digital signal, the auditory image using the Bose speakers was highly localized at the subjects' position, and the subjects needed to be careful about their head placement to maintain the correct position in the sound field.

Both the FCH and FCSF systems were calibrated in dB sound pressure level (SPL). For the FCH system, calibration was performed with a Knowles Electronics Manikin for Acoustic Research fitted with an ear simulator. For the FCSF system, calibration was performed with a Bruel and Kjaer 4164 microphone set at the position of the center of a subject's head with the subject absent. Daily pretest checks were performed to ensure that the system was producing the correct signal levels.

Subject Selection

Subjects (10 men and 10 women) were recruited from local universities and the greater Cincinnati area with flyers and newspaper advertisements. Subjects were between 18 and 45 years of age. Prospective subjects were interviewed on the telephone to assess their naiveté as hearing protector users. According to the ANSI S12.6 standard Method B instructions, subjects were disqualified if

(1) they had received personal instruction in the use of hearing protection devices;

(2) they had attended a lecture or viewed computer-based or video instruction on hearing protector usage in the past 2 years;

(3) they had participated in an experiment to measure noise reduction of hearing protectors within the past 2 years;

(4) they had worn earplugs more than 10 times and earmuffs more than 60 times in the past 2 years. (The ability to fit earmuffs is not influenced considerably by training or experience, thus more experience with earmuff use is allowed by the standard.)

Of 36 subjects brought in for testing, 16 failed to qualify for the study. During the first laboratory visit, subjects' hearing levels and middle ear status were assessed. Thresholds were bracketed with 5-dB steps and then determined to the nearest 1 dB. Subjects were required to have pure-tone air-conducted hearing threshold levels of less than 25 dB HTL re ANSI S3.6–1996[18] for the octave test frequencies 125 to 8000 Hz including 3000 and 6000 Hz. Subjects were required to have normal tympanometry values bilaterally, namely, middle ear pressure (−100 to +50 daPa) and static admittance (0.3 to 1.3 mL). Subjects who met these requirements were further required to demonstrate proficiency with the sound-field audiogram test system by producing three successive ears-open audiograms that had thresholds with a range of 6 dB or less at each frequency. (ANSI S12.6 Method B requires five training audiograms with the last three tests having a range of 6 db.)

Implementation of the Testing and Sequencing

The fitting instructions provided for the ANSI S12.6–1997 Method B[12] were used for all four SF methods. Subjects were provided with a placard with the manufacturer directions mounted on it and were given one practice fitting prior to any occluded testing. The experimenter read the instructions verbatim from the ANSI standard to the subjects prior to every fitting of the protectors.

Hearing protector testing was conducted on 2 separate days, approximately 3 hours per session. The test sequence for each subject was DSF_1, BCLB, and FCSF methods on the first day. On the second day the subjects were tested with the sequence DSF_2, FCH, and the EF method of ANSI S3.19–1974.[2] Two repetitions of occluded/unoccluded paired tests were performed for the DSF, BCLB, FCH, and FCSF methods. Three repetitions were performed for the EF method. Subjects were given new protectors for each series of occluded tests. Continuity of fit was maintained for occluded conditions during the test sequence for a given session (i.e., occluded DSF, BCLB, FCH, followed by unoccluded DSF, BCLB, FCH). Unoccluded and occluded trials were counterbalanced. Because the EF condition demonstrates the correct procedure for insertion of the Express earplug, this set of measurements was performed last to avoid a learning effect.

RESULTS

Figure 1 displays the grand mean real-ear attenuations for all subjects (solid line) and the average attenuations for individual subjects at each test frequency (filled circle). The greatest mean attenuations above 3150 Hz and smallest ranges at all frequencies of individual attenuations were found for the experimenter-fit data. Range was defined as the difference between the largest and smallest attenuations for a given frequency and method.

Figure 2 shows the standard deviations of the unoccluded and occluded hearing threshold levels for each test frequency within a method. The EF, DSF_1, and DSF_2 data exhibit nearly identical deviations at all frequencies for the unoccluded condition. The FCSF and FCH data exhibit deviations that are comparable at most frequencies, but are larger than the EF and DSF data. The BCLB deviations are markedly greater at all frequencies for the unoccluded condition. When the occluded condition is considered, little change is observed for the EF standard deviations. The FCH, BCLB, and DSF_1 occluded deviations appear to be slightly greater than the FCSF and DSF_2 deviations. If a learning effect were a factor, the FCH standard deviations should have been smaller than the FCSF. This was not the case. The reason the EF standard deviations are smaller is most likely due to the consistency of fit across the subjects and not due to a learning effect.

In Table I the real-ear attenuation means and standard deviations for each frequency and test method are presented. The average of the within-subject trials for a particular condition are reported as the means. The standard deviations were calculated from the within-subject means. For the EF data the averages were performed on all three within-subject trials. Otherwise, the SF data represent the average of two within-subject trials. Several trends are evident in the data. First, the EF data generally exhibited greater REATs and smaller standard deviations in comparison with the other methods. Second, the FCSF data at frequencies below 1000 Hz exhibited smaller REATs than other methods. Third, the BCLB method exhibited trends that were different across frequencies from the other methods. Compared with other methods, BCLB gave higher attenuations below 2000 Hz and lower attenuations above 2000 Hz.

The standard deviations for the BCLB method were also the greatest of the methods below 1000 Hz. Of the subject-fit REAT methods, the DSF_2 and the FCSF tended to have the smallest standard deviations, 5.6 to 8.0 dB. The FCH and BCLB methods tended to have larger standard deviations, 7.6 to 11.1 dB. Lastly, from examination of the manufacturer's test data, the experimenter fit data from this study exhibited smaller REATs than the manufacturer's at all frequencies and markedly so in the low frequencies, although the standard deviations are of similar magnitude. Detailed analysis of the EF data is considered in Franks et al.[9] for this hearing protector.

The attenuation data were analyzed with a repeated-measures, mixed model to identify the statistically significant differences between methods. Because the data for the BCLB did not include attenuation estimates at 125 and 8000 Hz, the analysis was performed in two parts. The first analysis included the data for all of the SF methods, but dropped the 125- and 8000-Hz data, whereas the second analysis excluded the BCLB data, but included the 125- and 8000-Hz data. EF data were not included because the consistency of fit was not maintained between the alternative fit-test methods and the experimenter-fit method as it was for the subject-fit methods.

The initial analysis began with a full model that included 2-, 3- and 4-way interactions:

$$a = (m + f + g + r) + (m{\cdot}f + m{\cdot}g + m{\cdot}r + f{\cdot}g + f{\cdot}r + g{\cdot}r) + (m{\cdot}f{\cdot}g + m{\cdot}f{\cdot}r + m{\cdot}g{\cdot}r + f{\cdot}g{\cdot}r) + m{\cdot}f{\cdot}g{\cdot}r,$$

where a = attenuation, m = method of measurement (BCLB, FCH, FCSF, DSF_1 DSF_2), f=frequency, g=subject gender, r=replication, m·f=the interaction between method of measurement and frequency, and so forth. Attenuation is a continuous variable, and all others are classification variables. Repeated-measures models with structured covariance matrices were fit using maximum likelihood as implemented in SAS 6.12 under PROC MIXED.[19,20] The choice of covariance structure did substantially affect inferences. A direct (Kronecker) product structure comprised of two unstructured matrices was chosen after likelihood ratio tests indicated that this type of covariance structure provided

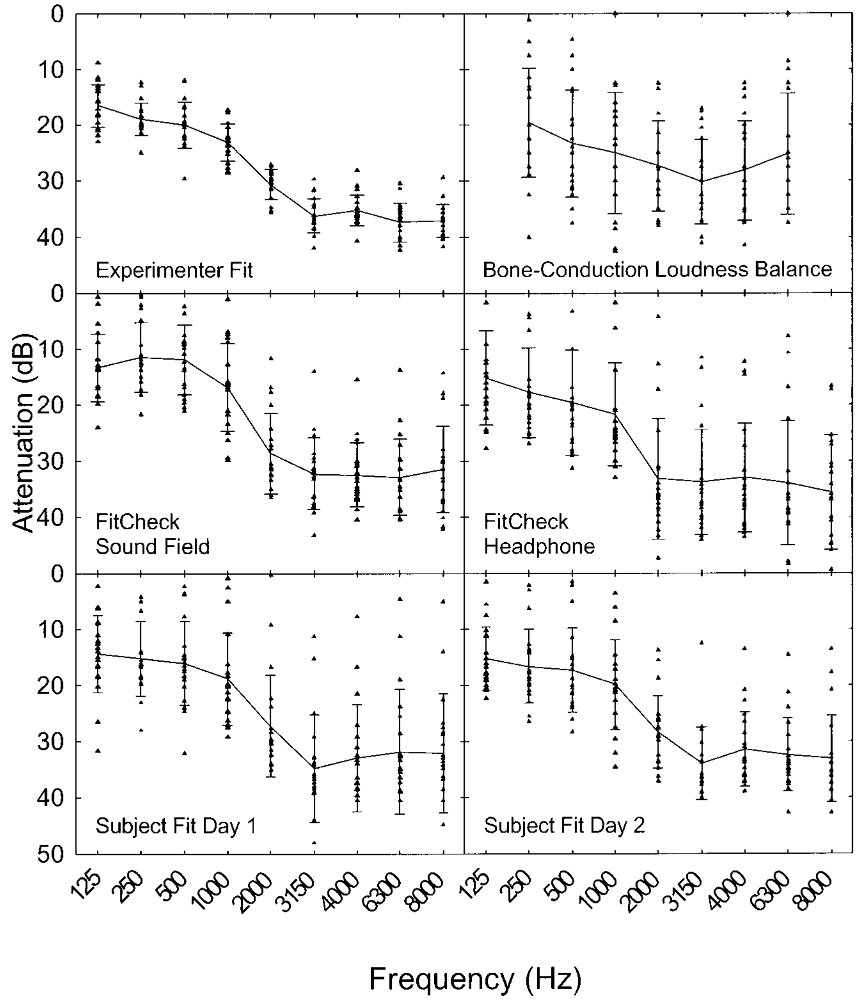

FIGURE 1. Average individual real-ear attenuations, mean group attenuations, and the ±1 standard deviation error bars plotted for six sets of measurements. The averaged real-ear attenuations were computed for each subject and plotted as black circles. The group means and standard deviations are depicted with the solid line and error bars. The results from each of the six measurements collected from 20 subjects are shown in different panels.

a better fit to the data than simpler alternatives (i.e., compound symmetry).

Significant effects ($p<.05$) were found for the method ($F=2.91(4,1340)$, $p=.0206$), frequency ($F=9.50(24,1340)$, $p<.00001$), method-by-frequency ($F=92.93(6,1340)$, $p<.00001$), and frequency-by-gender ($F=2.33(6,1340)$, $p=.0305$) interactions. The significant effects were expected for frequency and method-by-frequency, because the HPD attenuation is frequency dependent. Similarly, different methods of signal presentation could be expected to interact differently with the head acoustics for each gender and produce an interaction. However, when the BCLB data were dropped from the statistical analysis and the data at 125 and 8000 Hz were included, the frequency-by-gender interaction was no longer significant ($F=1.85(8,1375)$, $p=0.0641$). Method, frequency, and method-by-frequency remained significant. The frequency-by-gender interaction may result from differences in bone conduction between men and women. Dropping the bone-conduction data from the analysis removed that factor contributing to significance.

A contrast analysis of the means of the data revealed no significant difference ($p=.7058$) between the DSF_1 and DSF_2 REATs, so the other methods were compared with the combined results. The FCH mean data were significantly different from the DSF mean data ($p=.0070$). The FCH and FCSF means were significantly different from each other ($p=.0023$). The FCSF and BCLB data were not significantly different from the combined DSF data (FCSF: $p=.1240$; BCLB: $p=.8161$). The EF data were not included in the contrast analysis. When the BCLB data were dropped, and the data at 125 and 8000 Hz were included, the FCH mean remained significantly greater than the FCSF and DSF means.

DISCUSSION

The purpose of this study was to investigate how several field methods compared with the ANSI standard methods prescribed by ANSI S3.19–1974 and ANSI S12.6–1997.

Although linear regression between the fit-test data to laboratory data is possible, such analysis would not be appropriate. Specifically, the methods were performed in different sound rooms, used different equipment, and assessed threshold with different

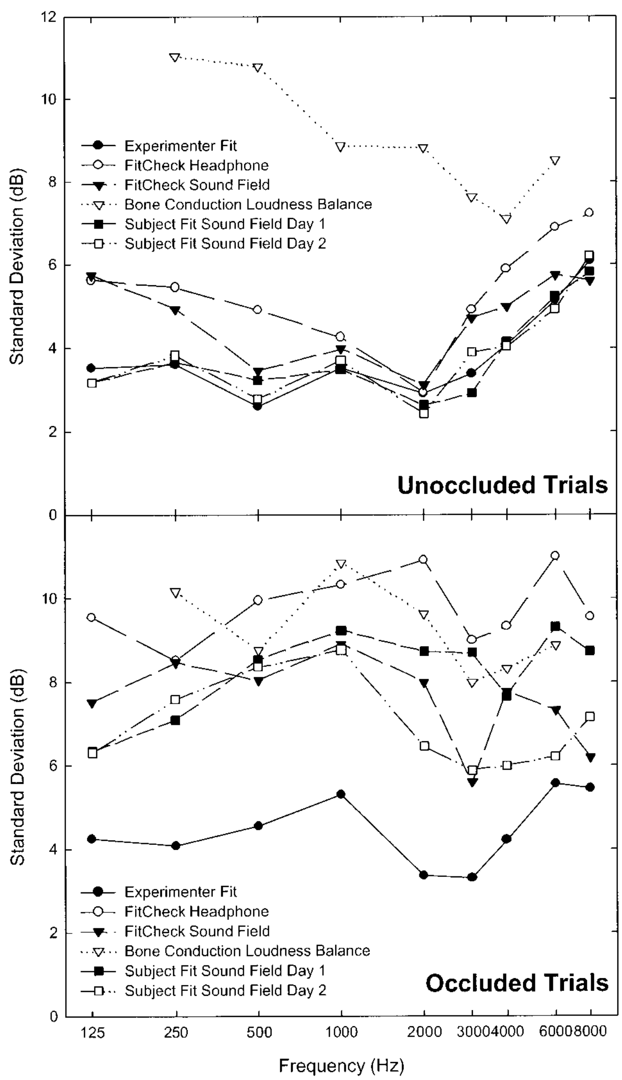

FIGURE 2. The standard deviations of the unoccluded and occluded trials for the real-ear attenuation estimates for the six methods

signal presentation paradigms. The purpose of this article was to determine whether the instrumentation and the proposed methods adequately estimate the attenuation of hearing protection when compared with a standard test method. Therefore, the data were analyzed without transformation.

The experimenter-fit method yielded the greatest attenuations and smallest standard deviations of the various methods considered here. Analysis of other REAT data has demonstrated that the within and between-subject repeatability were typically the greatest for the EF method.[21] The SF method generally yielded lower attenuation estimates but comparable repeatability with the EF method.[21] Field test methods should yield similar mean attenuations and variances for a given laboratory method and protocol. In this article the ANSI S12.6–1997 Method B subject-fit protocol was chosen to evaluate the field test methods. The methods exhibited comparable mean attenuations but had different results when the standard deviations for occluded and unoccluded thresholds were examined and slight differences for the standard deviations of the attenuation estimates (see Figures 1 and 2 and Table I).

DSF Method

The diffuse sound field was used to evaluate two hearing protector fitting protocols, SF and EF. The expectation was that the EF data would match those provided by the manufacturer; however, here they yielded less attenuation than the manufacturer's published data. The discrepancies of EF data with the manufacturer's data are discussed in detail in Franks et al.[9]

The subject-fit data were analyzed with a mixed model to identify differences between and within the methods. As mentioned previously, no significant differences between the data from the first and second days were identified for the DSF method. The possibility of a subject learning effect in a repeated-measures design is always a concern, thus subject performance was benchmarked against DSF_1 and DSF_2. In the absence of a day effect the data from the 2 days were pooled to permit an overall comparison between the DSF method and the other methods.

That continuity of fit was maintained across testing methods adds further substance to the comparisons. Had the earplug been removed at the conclusion of an occluded run for one of the tests and reinserted for the occluded run of a different test, it would have been necessary to include insertions as a random factor nested under subjects, itself a random factor.

BCLB Method

At face value, the BCLB method might be expected to produce some slight differences in mean bone-conducted attenuations due to occlusion effects because the bone-conducted reference frequency and the sound-field test frequency were the same. In general the mean BCLB real-ear attenuation data show the least discrepancy with the mean DSF_1 attenuation data at 2000 Hz, the middle ear resonance frequency. The mean BCLB attenuations are

TABLE I. Real-Ear Attenuation at Threshold Group Means and Standard Deviations (in dB) for Each Test Method and Stimulus Frequency

Frequency	Manufacturer's Data	Experimenter Fit	FitCheck Headphone	FitCheck Sound Field	Bone-Conduction Loudness Balance	Diffuse Sound Field Day 1	Diffuse Sound Field Day 2
125.0	31.6 ± 4.3	16.5 ± 3.9	15.1 ± 8.4	13.3 ± 6.1	—	14.3 ± 6.9	15.2 ± 5.6
250.0	32.1 ± 4.6	19.0 ± 2.9	17.8 ± 8.0	11.5 ± 6.3	19.5 ± 9.8	15.2 ± 6.7	16.6 ± 6.6
500.0	32.2 ± 4.8	20.0 ± 4.2	19.6 ± 9.4	11.9 ± 6.2	23.3 ± 9.6	16.0 ± 7.4	17.3 ± 7.5
1000.0	36.9 ± 4.0	23.1 ± 3.4	21.7 ± 9.3	16.8 ± 7.8	25.0 ± 10.8	18.8 ± 8.2	19.8 ± 8.0
2000.0	35.7 ± 3.3	30.6 ± 2.8	33.2 ± 10.8	28.6 ± 7.2	27.4 ± 8.1	27.3 ± 9.0	28.3 ± 6.5
3150.0	37.0 ± 3.3	36.2 ± 3.1	33.7 ± 9.4	32.2 ± 6.4	30.2 ± 7.6	34.8 ± 9.5	33.9 ± 6.4
4000.0	35.7 ± 4.2	35.2 ± 2.8	32.9 ± 9.7	32.4 ± 5.7	28.2 ± 8.9	33.0 ± 9.6	31.4 ± 6.7
6300.0	38.7 ± 5.1	37.4 ± 3.4	34.0 ± 11.1	32.8 ± 6.8	25.3 ± 10.8	31.8 ± 11.2	32.5 ± 6.6
8000.0	40.5 ± 3.4	37.1 ± 2.9	35.7 ± 10.2	31.5 ± 7.6	—	32.0 ± 10.7	33.1 ± 7.7

greater than the means of the other methods below 2000 Hz and are less than the other means above 2000 Hz. However, the large standard deviations for all of the subject fit methods render these differences to statistical obscurity.

The BCLB method was affected by the occlusion effect at low frequencies. The occlusion effect was largely due to changing the bone-conducted frequency to track the air-conducted stimulus. Rimmer and Ellenbecker[13] suggested that the bone-conducted frequency be held constant at 2000 Hz to minimize the occlusion effect, but this was not possible with standard clinical equipment. The unoccluded standard deviations for the BCLB method were largest for all frequencies. The increased variance of the BCLB method reduces the precision of the attenuation estimate and reduces the repeatability of a measurement.[11,21]

Loudness balance presented a different and more difficult psychophysical task to the subject as compared to threshold detection. The loudness-balance procedure required more administration time and yielded poorer repeatability, contrary to previous results from Rimmer and Ellenbecker (1997).[13] The BCLB data exhibited large standard deviations for equal loudness levels, overestimated the low frequency, and underestimated the high-frequency real-ear attenuation. If the rate associated with the Bekesy tracking procedure were reduced from 5 to 3 dB per second for the BCLB method, then the standard deviations for the equal loudness levels might have been reduced. The BCLB method lacked data at 125 and 8000 Hz due to the limits of the bone vibrator. Furthermore, although the BCLB method can be implemented in a laboratory setting, industrial implementation could be hampered by the lack of commercially available equipment for conducting this particular test. One advantage of the BCLB is the requirement for low background noise levels could be greatly relaxed because the loudness balance is conducted at a suprathreshold level, 40 dB HL.

FCSF Method

The FCSF method was implemented by supplementing a commercial system for measuring the REAT with amplifiers and loudspeakers in a small audiometric room. The method provided data that were consistent with the subject-fit DSF REAT method in the high frequency range (1000–8000 Hz). Although mean FCSF attenuations at 125, 250, and 500 Hz were lower, they were not statistically significant.

Several factors differentiate the FCSF test employed in the small sound booth with absorptive walls from the DSF testing in the large reverberant room. First, the FitCheck noise sources are static digital sounds stored as WAV files on computer disk and are not dynamically generated as the true random noise stimuli are for the DSF testing; that is, the FCSF stimulus noise is precisely the same for each pulse set. Spectral analysis of the WAV files revealed some small spectral splatter that was 30 dB down from the peak of the stimulus and thus inaudible, as the splatter was attenuated along with the stimulus.

Second, for DSF testing the large reverberant room was driven by three sets of speakers arranged to yield a diffuse sound field at the location of the subject's head re ANSI S12.6–1997.[12] Although each speaker set received the same stimulus, the reverberant conditions in the large room diffused the noise sufficiently at the center where the subject's head was located. The small test booth was not reverberant; therefore, three speakers with the same stimulus produced resonance and localized images in the sound field. With three sources in the room at ear level playing a coherent signal, it was possible to obtain an image of the pulsed noises in the center of the head for both ears open and ears-occluded conditions. Although this was a serendipitous finding that allowed normal-hearing subjects to optimally place their heads during testing, it would have been of no value to persons with asymmetrical hearing loss.

To minimize the resonance and the binaural imaging, the FitCheck system would need to produce and control three separate WAV files to drive each loudspeaker independently. After completion of the testing of the subjects for this study, the IAC 401 booth was reconfigured with different hardware so that each speaker was driven independently with narrow-band noise. This configuration provided a more diffuse image with less localized imaging, very similar to the experience in the large reverberant booth. Thus, use of the FitCheck system for sound-field testing in a small booth is not recommended unless it is modified so that three speakers are driven independently with uncorrelated noise. Recent results presented by Poulson[22] suggest that the diffusivity of the sound field is not a critical factor in estimating the REAT of a hearing protector.

Third, the FCSF system distorted the signal in the WAV file if the signal level was too high (>90 dB SPL). When calibrating the system, the preamplifier was adjusted so there was no audible distortion when the FitCheck attenuators were set to 0 dB. Although subjects for this study did not exceed the limits of the system, the hearing threshold levels of moderately hearing-impaired workers could routinely exceed the dynamic range of the equipment.

FCH Method

The FCH method measured more attenuation than the FCSF, DSF_1, and DSF_2 methods for most frequencies. These differences were statistically significant. Several explanations might resolve the differences with further research.

First, the surface area of the head that is stimulated in the occluded condition is larger using a sound-field presentation versus a headphone presentation. When a subject achieves a deep insertion, the energy transmitted via bone-conduction is comparable to the energy transmitted through the air-conducted pathway. If more energy is transmitted to the cochlea in the sound-field presentation, the occluded hearing threshold levels could be lower than the headphone presentation. Although this argument might be true for some earplugs, the attenuations measured for the Express did not approach the 40 and 50 dB limits where bone-conduction pathways become significant.[22,23]

A second effect could be related to the masking level differences inherent in headphone presentation of diotic stimuli. In the case of diotically presented pure tones masked by an uncorrelated noise source, Jeffress et al.[23] demonstrated a 0.2 dB improvement in average threshold levels of three subjects. This result suggests that noise-on-noise masking may not yield any appreciable improvement in hearing threshold levels. However, for other conditions, tone-on-tone masking, the improvements were dramatic, upward of 20 dB. Because the FCH stimuli were identical for both ears, the constant phase difference under headphone might have enhanced detection at threshold for the unoccluded condition. Earplugs change the relative phase and level of the stimulus at each ear such that the detection in the occluded condition is unaffected between the sound-field and headphone conditions. If these hypotheses were true, then the headphone would exhibit lower unoccluded thresholds than the sound field and comparable occluded thresholds and the FCH attenuations would be larger than the sound-field attenuations. This hypothesis is not something that can be ascertained from this data. Although every effort was made to accurately calibrate the signals, the FitCheck software was not intended to address such a question. Rather, the hypothesis requires careful investigation utilizing better psychoacoustic paradigms (e.g., two-alternative forced-choice, or yes-no paradigms) and in-the-ear calibration of the stimuli with probe tube microphones to permit comparison between the sound-field and headphone presentations.

Deployment of the Methods in a Real-World Setting

The FitCheck system with its large-cup circumaural earphones has some early adopters because it is easily used and provides almost instant feedback to the worker about the attenuation of his or her earplugs. However, increased distortion at high output levels may introduce errors in the FitCheck signal presentation levels, providing misinformation for workers who have hearing impairment and must use hearing protection. The use of a common WAV file may affect the comparability of the FitCheck results and diffuse field data measured according to ANSI S12.6–1997 Method B.[12]

The FCH standard deviations are larger than the FCSF standard deviations, potentially due to variance of fitting the earphones as well as fitting the earplugs. Although the FitCheck system for the FCH method may be used in almost any quiet room, the attenuation of the earcups is not stated, so that guidance as to what ''quiet'' means is not provided. If the system is used in the same sound room that is used for hearing testing, masking effects due to ambient noise should not affect thresholds.

The feasibility of using a FitCheck system modified for sound-field presentation has been demonstrated in this study. Further research is necessary to improve the sound-field environment in a single-person audiometric booth typical of those used for industrial testing. The output limitations should be remembered when testing workers with hearing loss. A sound-field system requires additional amplification and multiple incoherent noise sources to provide a high-level diffuse image. The sound-field implementation of the FitCheck system could test all manner of hearing protectors, earplugs, earmuffs, and ear canal caps, so that the best protector could be selected, fitted, and verified for each worker participating in a hearing loss prevention program.

The BCLB method is complicated and therefore difficult to deploy for routine evaluation of hearing protector evaluations. Subjects are required to judge air-conducted sound-field signals as louder or softer than bone-conducted reference signals, both of which are noise bands. Technicians who perform audiometry monitoring in most hearing conservation programs will likely have difficulty administering and interpreting the BCLB test. Subjects in this study had to be instructed multiple times before they understood the task for same-frequency loudness balances, whereas the noise-band threshold tasks were fairly straightforward.

CONCLUSION

In this study the SF method of ANSI S12.6–1997[12] was used in the DSF to obtain the REATs that were compared with the REATs from the FCH and FCSF methods and to the occluded-unoccluded loudness differences of the BCLB method when the same procedures were followed. Subjects were given only the manufacturer's instructions for fitting the earplug.

Because the point of deploying a field test method such as the FCH, FCSF, or BCLB is to see how a particular protector fits an individual worker, real-ear attenuations should be compared with the subject-fit DSF attenuations. At present, however, no manufacturers publish subject-fit DSF data, even though some of them have done the testing and have the data at hand. Comparing the FCH, FCSF, or BCLB data to the manufacturer's data published on the EPA NRR label can lead to the incorrect conclusion that the worker is not using the protector ''correctly.'' Berger et al. (1996)[6] have shown that it is unrealistic to expect actual worker outcomes to approximate experimenter-fit DSF values. Berger et al. (1998)[10] also showed that the subject-fit DSF data are highly predictive of the REATs achieved by well-motivated workers.

In continued efforts to improve hearing loss prevention in the workplace, the capability to measure personal attenuations of hearing protection devices now exists. With appropriate modeling of the attenuation data for a population of subjects, statistical classification of the quality of fit can be determined and assist the hearing conservationist in the training of workers required to use hearing protection. These new field-test methods have the potential for measuring individualized attenuation values instead of relying on single number estimates of attenuation placed on hearing protectors.

However, these field procedures need to be modified to resolve errors and quirks. The manufacturers of hearing protection need to test their products in accordance with the SF method of ANSI S12.6–1997[12] and provide the information to hearing loss prevention professionals and to workers who must use their products to prevent noise-induced hearing loss.

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