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Bone conduction loudness balance (BCLB), a new method for determining the attenuation of hearing protective devices (HPDs), was evaluated. When using BCLB for earplug testing with headphones, pure tones of equal frequency can be used for both the air conduction (AC) and bone conduction (BC) sounds with reasonable accuracy. Using BCLB with an external loudspeaker as the AC sound source makes it impossible to use pure tones of equal frequencies since the occlusion effect will cause an overestimation of attenuation at frequencies under 2000 hertz. A practical way to minimize the occlusion effect is to use a constant frequency noise band as the BC sound against which AC noise bands of varying frequency are balanced. Comparisons of mean A- weighted attenuation for broad band noise of various frequency distributions showed agreement generally within 1 decibel between BCLB and real ear attenuation at threshold (REAT), for earplugs, earmuffs, and earmuffs with earplugs. No significant interference was noted by background noise up to a level typical of industrial audiometric testing environments, 35 decibels-A. No significant differences were noted in BCLB and REAT with regard to administration time and repeatability. The BCLB was found to be accurate, reliable, and practical for determining attenuation for all common types of HPDs.

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LIST OF ABBREVIATIONS

AC	Air conduction
BC	Bone conduction
BCLB	Bone conduction loudness balance
dBA	Decibels, A-weighted
HPD	Hearing protective device
NCB	Balanced Noise Criteria
NRR	Noise Reduction Rating
REAT	Real ear attenuation at threshold

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SIGNIFICANT FINDINGS

A new method for determining the attenuation of hearing protective devices (HPDs) called bone conduction loudness balance (BCLB) was evaluated and improved in a three phase process. Throughout the evaluation, the method was compared to the standard procedure, real ear attenuation at threshold (REAT), both in terms of the attenuation values measured and of practical aspects of administration. The overall general conclusion is that BCLB has been shown to be an accurate, reliable, and practical method for determination of attenuation for all common types of HPD, and that it has good potential for use as a field method due to its resistance to background noise and applicability to all HPD types. In addition, the following more specific conclusions have also been reached:

a. A practical instrument for implementation of BCLB is a personal computer with a digital-to-analog sound processor to generate and control the bone conduction (BC) and air conduction (AC) sounds presented to the HPD wearer for balance.

b. When BCLB is used for earplug testing with headphones to generate the air conduction sounds, pure tones of equal frequency can be used for both the AC and BC sounds with reasonable accuracy since the occlusion effect is minimized by the constant presence of the headphones.

c. When BCLB is used with an external loudspeaker as the AC sound source, pure tones of equal frequencies cannot be used since the occlusion effect will cause an overestimate of attenuation at frequencies below 2000 Hz.

d. The use of a constant frequency (2000 Hz) noise band as the BC sound against which AC noise bands of varying frequency are balanced is a practical way to minimize the occlusion effect. Balancing the loudness of noise bands of different frequencies is somewhat more difficult subjectively than balancing pure tones of equal frequency, but no more difficult than determining threshold with noise bands.

e. For slow-recovery, expandable foam earplugs, the mean attenuation at specific frequencies measured by BCLB agreed with REAT testing within 1 dB at frequencies of 1000 Hz and below and within 4 dB at higher frequencies. In addition, approximately 95% of all individual comparisons at individual frequencies for all subjects agree within ±10 dB. f. For other types of HPD tested (earmuffs, canal caps, and earmuffs combined with earplugs), the mean attenuation at specific frequencies measured by BCLB agrees with REAT testing within 3 dB at most frequencies tested, with the greatest mean difference at any frequency being 4.6 dB. In addition, approximately 88% of all individual comparisons at individual frequencies for all subjects agree within ±10 dB.

g. Comparisons of mean A-weighted attenuation for broad-band noise of various frequency distributions showed agreement generally within 1 dB between BCLB and REAT for earplugs, earmuffs, and earmuffs combined with earplugs.

h. For only one type of HPD tested (canal caps), did BCLB consistently find a higher attenuation than REAT (about 3 dB) both for individual frequencies and for broad-band noise. This difference may be attributed to the existence of a small occlusion effect at 2000 Hz by this type of HPD, suggesting the possible need for a higher frequency sound (3000 Hz) as the BC test signal.

i. BCLB results were not significantly affected at any frequency by background noise up to a level typical of industrial audiometric testing environments (35 dBA). The results at 2000 Hz and below were not affected by background noise up to the level typical of a "fairly noisy" office (53 dBA), but for frequencies of 4000 Hz and 8000 Hz, the results were unclear, with either interference by the background noise or the test procedure being possibilities for the unexpected outcomes.

j. The comparison of BCLB and REAT with regard to administration time and repeatability showed no significant differences. The actual mean time to determine balance at each frequency varied from 29 s to 76 s, depending on the stringency of the criteria for achieving a consistent result. These times were not significantly different from the times to determine threshold using similar consistency criteria. Repeatability from one successive test to the next was also not significantly different for BCLB and REAT.

Even for the case in which a statistically significant difference was shown, the disagreement is of little practical consequence, especially considering such factors as the normal uncertainty in measurement of noise exposure, the day-to-day fluctuation in the exposures themselves, and the variation in attenuation that might be expected each time the HPDs are used. A field attenuation measurement procedure that is both feasible and accurate for the large majority of situations would be far superior to the common practice of estimating attenuation by halving of the laboratory-derived Noise Reduction Rating, regardless of HPD type or ability of the wearer to achieve a proper fit. BCLB has been shown to be accurate for all types of HPD normally used on the job, especially for earplugs which are subject to the most attenuation uncertainty due to fitting variations.(1-4)

USEFULNESS OF FINDINGS

Once standardized and fully developed, BCLB would have a number of useful applications as part of an occupational hearing conservation program. One significant benefit would be its use in the selection of HPDs and user training in proper wearing techniques. For example, after a worker chose one or more particular HPDs that he or she was comfortable with, an abbreviated BCLB test with either a limited range of frequencies or a broad-band noise could be used to determine which of the HPDs was best suited for the anticipated noise exposure. The user could be taught the proper HPD usage and receive immediate, quantitative feedback about the HPD performance. The relative effectiveness of different HPDs would be a factor that both workers and hearing conservation program administrators could take into account when choosing HPDs for specific situations. A clear demonstration of the protection offered by the HPD might well have a positive effect on the wearer's inclination to use the protection.

Detailed information about HPD performance at the various frequencies would be especially useful for hearing impaired workers who need to have protection specifically tailored to their noise exposure to avoid excessive attenuation that would significantly hinder their communication ability.(5) The same sort of detailed information is needed for workers exposed to very high noise situations in which the use of broad-band, generalized attenuation data such as the Noise Reduction Rating may not be a good enough indicator of the true performance to allow the HPD to be confidently used.

Another use of BCLB as an element of the hearing conservation program would be to make it a part of the performance audit of the program. For example, instead of an inspector simply observing whether or not HPDs are used, she could take workers off the job for brief, unannounced attenuation assessments at random intervals (perhaps once or twice per year). Measurements indicating that the HPDs were not adequately protecting the users for their specific noise exposures would be a persuasive argument for implementation of other noise control measures or for improvement in the HPD utilization, whether for a specific worker or throughout an organization. On the other hand, measurements showing an adequate amount of attenuation would be helpful in making a reliable assessment of whether a worker's hearing loss was work-related or not.

In addition to the use of BCLB for field testing the performance of conventional HPDs such as earplugs, earmuffs, and canal caps, BCLB may also be applicable for tests of other types of HPDs or noise situations for which REAT is not appropriate. One such application would be to determine the performance of non-linear HPDs which are intended to increase attenuation as the impinging noise rises above certain high levels. HPDs of this sort have orifices, diaphragms, or valves that are intended to allow speech and similar lower level sounds to penetrate and be clearly heard but at the same time to block transmission of high intensity noise. REAT testing does not work with these HPDs since the sounds are above threshold, but BCLB should be applicable.

Another related situation is the use of normal, linear HPDs against impulse or impact noise. There is conflicting evidence regarding the applicability of attenuation data measured with low-level, continuous sounds to the situation involving high-level, impulsive noise. Some studies have shown that the attenuation measured with REAT is also applicable to impulse noise whereas other work indicates that there may be significant differences.(6) BCLB could be adapted to impulse sound testing at high levels.

A third type of HPD for which BCLB testing could be particularly suited is the active noise cancellation device. This sort of HPD provides attenuation at low frequencies by means of an electroacoustic feedback system which generates a reverse-phase noise in the earmuff cavity to reduce the sound level reaching the ear by destructive interference. REAT testing may be appropriate for these HPDs since the residual noise of the sound cancellation system would mask the threshold levels of the subject, and objective testing results depend on the microphone location within the earmuff cavity.(7)

Assuming that any technical problems limiting implementation of BCLB could be overcome, some other obstacles to its use would remain. Most of these problems are not unique to BCLB, but are associated with other field procedures as well. One limitation of any type of testing is the concern that even though a particular HPD gives a certain degree of attenuation when tested after initial fitting, it might be expected to become looser and less protective after a period of use due to head and jaw movements, particularly talking and chewing. For some insert HPDs (earplugs), decreases in attenuation of 5 to 10 dB have been documented after several hours of use, although generally not for slow-recovery foam earplugs that have been properly fitted.(8) A related concern would be that the HPD user would be more careful in wearing or fitting the HPD when about to be tested than in normal use, thus overestimating the attenuation to be normally expected. A similar situation arises in the fit testing of air purifying respirators during training or wearer certification. Because of the expectation of poorer fit later, the measured protection factor for respirators is normally reduced by a factor of 10 when predicting the degree of actual protection on the job. Such a safety factor could also be applied to HPDs which should probably be device-specific or frequency-specific factors. Earmuffs, for example, should be less likely to decrease in attenuation than would many kinds of earplugs.(1)

In conjunction with or perhaps in place of a safety factor for better predicting real-world HPD performance from attenuation measurements, unannounced testing could also be done at times when the HPD had been in place for a long period to more conservatively evaluate performance. This strategy would also assess the ability and efforts of HPD users to achieve a good fit when they were not expecting to be tested. If workers are assigned HPDs that protect adequately only if fitted in a way that is too much trouble for normal and ordinary use, then other HPDs should be substituted which will actually be worn in a way that provides the necessary attenuation.

As with any other subjective test (including REAT), a limitation of BCLB is that it relies on careful and candid subject response. If the HPD user is distracted, rushed, poorly motivated to wear HPDs, resentful of any aspect of the hearing conservation program, or, in general, is not disposed to be fully cooperative with the BCLB test, then the test will not be able to correctly measure HPD performance. This problem is not unique to BCLB or REAT, of course; it would equally apply to any subjective test such as audiometric testing or qualitative respirator fit testing. For all such tests, usage must be only in concert with all other aspects of the protective program, including proper utilization of other controls, periodic training, and appropriate motivation.

Another human factor more specific to BCLB to be taken into consideration is that of hearing impairment in the HPD wearer which could make the BCLB test more difficult (or impossible) to administer. The HPD wearer has to be able to clearly hear the BC test signal (normally at 2000 Hz). A substantial hearing loss at that frequency would mean that the BC sound level would have to be increased accordingly, up to the limits of the BC vibrator. The external AC sounds would also be increased to balance the perceived BC level; when coupled with a high attenuation, the sound generating apparatus might not be able to create the necessary sound level. In that case, BCLB would be able to only set a lower limit on HPD attenuation, which would itself be useful information. The hearing loss of some individuals might be high enough to preclude their being tested with BCLB at all. Other individuals may not be able to make judgments about loudness balance reliably enough to make the process work. Certainly it is likely that BCLB would not be able to test HPD attenuation for every individual, but it is reasonable to expect that such cases would be uncommon. In the present study, the maximum hearing loss in test subjects was about 30 dB at 2000 Hz, and it is estimated that hearing losses up to 40 dB or more would be testable. Only about 10% to 15% of the U.S. population even by age sixty has 40 dB or more of hearing loss at 2000 Hz, so the percentage in the population at large would be much less,(9) although the younger age of the noise-exposed working population would be at least partially offset by the higher expected levels of hearing loss at any particular age.

Ultimately, the prevention or minimization of noise-induced hearing loss is the goal of an occupational hearing conservation program. Such a program encompasses the diverse elements of noise monitoring, noise control, worker training, and regular hearing assessments, each of which is important in the success of the program. HPDs play a vital role in hearing conservation as an alternative to other noise control techniques that in many situations may be less feasible both technically and economically. Any improvements which would help ensure HPD effectiveness would be a significant step forward in the effort to prevent occupational hearing impairment. As a practical, reliable and accurate means of determining HPD performance, BCLB has the potential to be a key component of the hearing conservation effort.

ABSTRACT

A new method for the measurement of hearing protective device (HPD) noise attenuation was developed and evaluated. The procedure, bone conduction loudness balance (BCLB), utilized pulsed sounds delivered alternately by a bone conduction vibrator on the forehead of the HPD wearer and by a loudspeaker outside the HPD. The bone conduction sound was maintained at a constant level and frequency (high enough to avoid the occlusion effect) and the air conduction sounds (1/3 octave bands of noise) were varied in level by the HPD wearer to achieve a subjective impression of equal loudness. The difference in level between the sounds required to balance with the HPD on or off was defined as the attenuation.

After preliminary feasibility testing, the BCLB procedure was compared to the standard method, real ear attenuation at threshold (REAT) as specified by ANSI Standard S12.6-1984, for 32 subjects. For expandable foam earplugs, the mean attenuation measured by BCLB agreed with REAT within 1 dB below 2000 Hz and within 4 dB at higher frequencies. In addition, approximately 95% of all individual attenuation comparisons at individual frequencies agreed within ±10 dB. For other types of HPD tested (earmuffs, canal caps, and earmuffs combined with earplugs), the mean attenuation agreement was within 3 dB at most frequencies and within 5 dB at all frequencies. Comparisons of mean A-weighted attenuation by BCLB and REAT for broad-band noise of various frequency distributions showed no statistically significant differences for all HPD types tested, except for canal caps, for which BCLB measured 3 dB higher attenuation than REAT. BCLB results were not significantly affected by background noise at a level typical of industrial audiometric testing environments (35 dBA) nor were the results at 2000 Hz and below affected by background noise at the level of a typical office (53 dBA). No significant differences were observed between BCLB and REAT regarding administration time or repeatability. It was concluded that the BCLB method is well suited for field use due to its applicability to all HPD types, resistance to background noise effects, and good agreement with REAT.

INTRODUCTION

Hearing protective devices play an important role as an element of hearing conservation programs designed to prevent occupational hearing loss. They have the potential to provide sufficient protection to reduce nearly all noise exposures to acceptable levels, but many studies have shown that the degree of protection actually achieved on the job is usually much less than the laboratory determined noise attenuation. One way of dealing with this problem would be a field test to actually measure the amount of protection actually achieved by an individual worker wearing a particular HPD. However, all existing field procedures have limitations which make them unlikely to achieve widespread use.

The ideal field testing method for measurement of HPD attenuation would apply to all kinds of HPDs and could be performed without the need for a special environment or elaborate equipment. In addition, it would be comparable for any individual worker to the standard test, Real Ear Attenuation at Threshold (REAT), and capable of being performed at any point in the work day without disturbing the fit of the HPD. Field testing of HPD performance could be useful in training, in selection of the best device for the individual, and in assessment of the effectiveness of the hearing conservation program in general. If the actual attenuation of a particular HPD for a particular worker could be assessed, then workers would have more choices in their selection of effective protectors and would be more assured of avoiding hearing loss. The development, testing, and evaluation of a new attenuation measurement procedure which appears to meet these criteria is the subject of this study.

The proposed field procedure is based on the use of loudness balance, an alternative paradigm to the threshold difference method of HPD attenuation measurement. This sort of procedure requires the HPD wearer to adjust the level of an airborne sound to be the same loudness as a reference, fixed-level sound which is not affected by the presence of the HPD. The wearer then removes the HPD and adjusts the airborne sound to balance the reference sound again. The difference in the level of the airborne sound which balances the reference sound with and without the HPD is therefore the attenuation of the HPD. For example, if an airborne sound at 1000 Hz must be adjusted to a level of 50 dB to balance the reference sound with the HPD in place and to a level of 35 dB to balance the same sound when the HPD is removed, then the attenuation of the HPD at 1000 Hz for that wearer is 15 dB (50 dB - 35 dB).

Loudness balance has previously been used in various forms to measure HPD attenuation,(10-13) but a new and potentially useful way of implementing the concept would be to provide the reference sound by means of a vibrating transducer held against the HPD wearer's head so that sound reaches the ear by means of bone conduction (BC) rather than the usual air conduction (AC) route. The BC sound will thus bypass the HPD and be unaffected by it. This variant of loudness balance, called bone conduction loudness balance (BCLB) is not known to have been described in the literature and is the subject of this study.

Conceptually the BCLB procedure is very simple. First, a brief pulse of sound is delivered to the inner ears of an HPD wearer through a transducer placed in contact with the head (BC pathway). Next, another brief sound pulse of the particular frequency to be tested is presented externally to the ear and the HPD by either headphones or a loudspeaker (AC pathway). The listener compares the loudness of these two sound pulses and adjusts the AC sound level to make their apparent loudnesses more equal. The two pulses and the adjustment are repeated as many times as necessary until the listener judges that their loudnesses are balanced or equal. The process can be repeated at a variety of frequencies to cover the required range, and the AC sound levels where balance is attained are noted for each frequency. If the HPD is then removed and the entire procedure repeated, a lower level AC sound at each frequency will be required to balance the bone conducted (BC) sound (which is held at a constant level). The decrease in the level of the AC sound required to balance the BC sound when the HPD has been removed is a measure of the HPD attenuation.

Compared to the standard REAT method, the BCLB procedure should be equivalent in that it can be applied to all categories of HPD and superior in that it would not require a low noise environment. When compared to the modified REAT method using headphones that is sometimes used in the field (REAT-HP), BCLB has the significant advantage of working for all HPD types (not just earplugs) as well as less severe background noise requirements. Because a sound field can be used, BCLB should be more compatible with the standard of REAT (which uses a sound field for the test signals) than is the modified REAT-HP. Testing with a diffuse sound field in which the sound impinges on the head and ears from all directions is clearly more representative of actual use conditions than is testing with headphones which limit the sound direction and area of impingement.

Despite the potential advantages of BCLB, there are also some problems to be overcome, or at least considered. One important limitation of bone conduction as an element of the procedure is the occlusion effect, an increase in the sensitivity of the inner ear to bone conducted sound when the air conduction pathway is blocked. The increase is thought to be due to more effective stimulation of the eardrum by ear canal vibrations when the normally open end of the canal is closed.(6,14) The result is that bone conducted sound vibrations are more efficiently transmitted to the inner ear so that the BC threshold is substantially lowered for some frequencies when the ear is occluded (blocked or covered) by any sort of HPD or even the headphones used for testing. At 250 Hz, for example, the occlusion effect may cause 20 dB or more in threshold reduction when HPDs are in place compared to the threshold when the open ear is tested.(6,14,15) Thus a BC sound, particularly near the threshold of hearing, may sound louder when the ear is occluded than when it is open. Since the essence of the BCLB test is that the BC sound is to be at a constant level of loudness against which the AC sound is compared, the occlusion effect is certainly a problem which must be overcome.

Fortunately, the occlusion effect decreases with increasing sound frequency and is usually consider to be negligible above about 1500 Hz.(15) If the bone conduction sound is above that frequency, the presence of an ear covering does not increase the apparent loudness of the BC sound so loudness balance judgments and the attenuation measurements should not be affected. One strategy to deal with the occlusion effect therefore would be to only use the method for high frequency measurements and judge HPD effectiveness on that basis. A limited range of frequencies has been used to predict broad-band attenuation,(16) but it is not particularly desirable since HPDs are less effective below 2000 Hz. Another solution is to maintain the BC sound at or above 2000 Hz and allow the AC sound to range over all frequencies of interest. This would require the loudness balance to be performed between two sounds of different frequencies, generally a more difficult problem than balancing sounds of the same frequency.(17)

Another potential problem for the BCLB procedure concerns the difficulty of the loudness balance process. For BCLB, the subject is required to compare the loudness of two sounds (possibly of different frequencies) and to adjust one of them until the two are equally loud. In the REAT procedures, the subject is only required to decide if he or she can perceive a sound or not. It may be that the balance process will be more difficult than the simple "yes-no" choice of threshold determination. Also, industrial workers who would be tested would already be familiar with threshold testing since that is the basis of their annual hearing test.(18) However, loudness balancing is a commonly used technique in the audiometric assessment of certain types of hearing disorder, so it is certainly not an unknown process.(17) Until experimentation can compare the difficulty of the two processes, the loudness balance difficulty remains only a hypothetical problem.

A third potential problem with BCLB is the requirement for additional instrumentation that is not currently used or readily available in industrial hearing conservation programs. The need to generate two channels of sound with independent control of sound frequency and intensity is outside the capability of the normal industrial audiometer. However, the personal computer with two-channel, analog-digital sound capability is now available at a reasonable cost with the additional benefit of being able to process and store the data generated by the process. Such capabilities are now available even in very small, "notebook" computers which should be ideal for field use.

The overall objective of this study was a feasibility assessment of the bone conduction loudness balance (BCLB) procedure for HPD attenuation measurement. The study was done in three phases as shown in Table 1 and described below:

Phase 1

a. Preliminary feasibility evaluation of BCLB using a two-channel diagnostic audiometer as the test signal source with one subject, 3 different earplug types, and comparison to REAT using headphones. Both pure tones and noise bands were used in the BCLB process, with pure tones only for the REAT procedure.

b. Modification of a personal computer with a digital-analog sound processor card and appropriate software to serve as the test signal source. Further feasibility evaluation of the BCLB procedure and equipment using the new instrument, 4 subjects, 1 standard earplug type, 5 frequencies (250 to 4000 Hz) and comparison to REAT using headphones. Again, both pure tones and noise bands were used in the BCLB process, with pure tones only for the REAT procedure.

Phase 2

Modification of the software and procedures based on the results of Phase 1 to improve the accuracy and consistency of the results and to allow testing under a broader range of frequencies. Additional evaluation of BCLB using the modified instrument and procedures, 8 subjects, 1 standard earplug type, 5 frequencies (125 to 8000 Hz) and comparison to the standard REAT method using sound field testing in a low-noise environment. Also, the effect of elevated background noise on the attenuation results was also evaluated. Noise bands were used for both the BCLB and REAT procedures.

Phase 3

Modification of the software and procedures based on the results of Phase 2 to improve the speed and simplicity of the method. Additional evaluation of BCLB using the modified instrument and procedures, 24 subjects, 4 different HPD types (earplug, earmuffs, canal caps, and earplugs combined with earmuffs), 9 frequencies (125 to 8000 Hz) and comparison to the standard REAT method using sound field testing in a low-noise environment.

Table 1 Study Design for Evaluation of Bone Conduction Loudness Balance

Designation and purpose
1 - Feasibility of method in general
Feasibility of computerized instrumentation
2 - Comparison with standard procedure for earplugs
Effect of elevated background noise
3 - Extended comparison for full range of HPD types
Extended comparison for full range of frequencies

Number of Subjects
1 - 4
2 - 8
3 - 24

HPD Types
1 - 1 earplug type (expandable foam)
2 - 1 earplug type (expandable foam)
3 - 1 earplug, 1 earmuff, 1 canal cap, earplug/earmuff combined

Frequencies (Hz)
1 - 250, 500, 1000, 2000, 4000
2 - 125, 500, 2000, 4000, 8000
3 - 125, 250, 500, 1000, 2000, 3150, 4000, 6300, 8000

Comparison procedure
1 - REAT (headphones)
2 - REAT (sound field)
3 - REAT (sound field)

EXPERIMENTAL PROCEDURE (PHASE 1)

For the initial feasibility assessment, the BCLB procedure using headphones was compared to the REAT method using a personal computer with an analog-digital sound card to generate the test signals and control the sound levels. This instrument was used for both the BCLB-HP and REAT-HP attenuation tests for a single earplug with four student volunteers as the test subjects.

An IBM-compatible 80286 personal computer (Best LCD Portable®) was used with an added analog-digital sound processor card (Sound Blaster 16®). Noise bands and pure tones generated from an audiometer (GSI 1615®) were recorded digitally (with 8 bits of resolution and at a sampling rate of 22 kHz) and stored as digital files which could be replayed by the computer as needed. Two sets of files were created, one for pure tones and one for noise bands. For the pure tones, the file for each frequency consisted of 0.5 s with the tone on the right channel and silence on the left channel followed by 0.5 s with the tone on the left channel and silence on the right channel. For the noise bands, the file for each frequency consisted of 0.75 s of a 1/3 octave noise band (2 kHz center frequency) on the right channel and silence on the left channel followed by 0.5 s of silence on the right channel and a 1/3 octave noise band at the frequency of interest on the left channel. The BC sound using the noise bands was of longer duration than the AC sound in order to aid the subject in the identification of which was the reference sound. For both kinds of file, there was also a command that the file was to be "played" endlessly so that only 1 or 1.25 s of digital sound data had to be stored. The frequencies covered were 4, 2, 1, 0.5, and 0.25 kHz.

A program was written using the Basic language (Q-Basic®) to play the sound files as necessary to accomplish the BCLB and REAT procedures. The program incorporated as sub-routines various commercial programs that were supplied with the sound card to play the sound files and to control the sound level output based on the subject input. The sound level could be varied in 2 dB steps (although 4 dB steps were used in this study phase to speed the balance process and to maintain compatibility with the first phase which used 5 dB steps). The internal amplifier on the sound card was not used since the output was adequate to drive the headphones (TDH-50P®) and the BC transducer at required sound levels. The maximum sound pressure level within the linear range for the headphones was 85 to 90 dB at the various frequencies. The sound output of the headphones was measured with a GenRad Model 1988® octave band analyzer and a GenRad Model 9A® coupler. The measured sound levels over the linear range were within 0.5 dB of the predicted values obtained from a single calibration value and the number of 2 dB steps added or subtracted by the sound processor.

The BC transducer, a standard audiometric BC vibrator (Radioear B-71®) was held to the subject's forehead with an adjustable fabric headband with a hook and loop fastener. A hard plastic plate (10 cm^2) was held between the BC transducer and the forehead for greater comfort since the small contact area of the transducer itself (1.5 cm^2) caused uncomfortable pressure after a few minutes of use. Subject response was indicated by way of three push-button, momentary-contact switches mounted in a small, plastic box and connected to the "game" port of the computer. The subject held the box in his or her hand and pushed the appropriate switch to either (1) increase the level of the AC sound, (2) decrease the level, or (3) indicate that the two sounds were loudness balanced. For threshold testing, the subject pushed switch (3) to indicate that the sound was audible and just above an inaudible level. The switch box also had jacks for connection of the headphones and the BC transducer to the sound card in the computer.

In the BCLB mode, the program was set to first play the 4 kHz file (in either pure tones or noise bands, whichever was chosen). The right channel, to which the BC transducer was connected, was set to a level which did not change throughout the course of the test. The left channel, connected to the headphones, was initially set to a level well below the loudness of the BC sound. As the subject pushed the "increase" button, the AC sound increased in 4 dB steps. Each subject was instructed to increase the level of the variable sound until it was louder than the fixed level sound. He or she was then to alternately decrease and increase the sound level as many times as necessary until a level was reached at which he or she was confident that the two sounds were of equal loudness, in his or her best judgment. The subject then was to push the "satisfactory" switch, at which time the AC sound pressure level was recorded. The program then advanced to the next frequency in the series and the subject repeated the balance process.

In the threshold testing mode, only the AC channel was activated and the initial tone was continuously pulsed at a level about 30 dB above normal threshold. The subject was told to use the "decrease" switch to lower the sound level to the point of inaudibility and then increase it to a level where it was just perceptible. He or she was to repeat the decrease and increase until he or she was confident that the sound was at the minimum audible level. The subject then pushed the "satisfactory" switch, at which time the AC sound pressure level was recorded and the program switched to the next frequency and the threshold determination was repeated.

The subjects were all students (3 male, 1 female) with hearing in the normal range (as determined from the open-ear threshold testing) and no previous experience with the type of earplug used or with loudness balance testing. Each subject was first given a demonstration of the loudness balance procedure using a loudspeaker for both channels of sound and pure tones for the test signal. The subject was shown how to use the controls to increase and decrease the variable sound level until it appeared to equal the loudness of the fixed level sound. Threshold determination was demonstrated in a similar way. Next, instruction in the use of the expandable foam earplugs was given by demonstration, and the subject was instructed to insert an earplug in the right ear. The experimenter did not assist with the insertion or require any repeat of the insertion if it appeared to fit poorly since the objective of the experiment was to evaluate the measurement procedure over the full range of earplug fits, rather than just the optimum fit.

For half of the tests, the testing process was done first with the earplug inserted and then with it out; for the other half the order was reversed. For both groups, to begin the test, the BC transducer was placed on the forehead with the subject fastening it in place with instructions to make it "snug, but not uncomfortably tight." Next the headphones were put in place by the experimenter, but the subject was allowed to adjust them for comfort. The testing process was then done for all three methods (REAT with pure tones, BCLB with pure tones, and BCLB with noise bands) with the method order varied systematically to ensure that each method was used the same number of times in each position in the sequence. For each method, frequencies were tested in the order 4, 2, 1, 0.5 and 0.25 kHz. After all three methods were used for all of the test frequencies, they were repeated in the same order. The headphones were then removed, the earplug removed or inserted by the subject as necessary and the REAT and BCLB procedures were done twice more, in the same order as before. The time for the entire session, including training, was approximately one hour.

The same process, except for the training, was repeated on a second day (within 1 or 2 days). The order of methods was changed as was the order of earplug use. For each of the 5 frequencies and for each of the 3 procedures, loudness balance or threshold determination was repeated a total of 8 times, making a total of 120 determinations for each subject. Each pair of repeated determinations was averaged and the averaged value for the open ear was subtracted from the averaged value for the occluded ear to calculate the attenuation. Thus there were 30 values of attenuation measured for each of the 4 subjects (5 frequencies x 3 methods x 2 days) for a total of 120 attenuations or 40 for each method which could be compared.

RESULTS AND DISCUSSION (PHASE 1)

Figures 1 and 2 plot the individual attenuation measurements by the two BCLB procedures against the attenuation measured by the REAT test for the same earplug insertion. The correlation coefficient between BCLB and REAT measurements was 0.767 for the pure tone (equal frequency loudness balance), and for the noise band BCLB method (un-equal frequency loudness balance), the correlation with the REAT measurements was 0.829. The linear least-squares regression of REAT with BCLB also demonstrates slightly better explanation of the REAT variation by the noise-band method ($R^2 = 0.69$) than by the pure-tone method ($R^2 = 0.59$), but the regression lines plotted on Figures 1 and 2 demonstrate relatively poor agreement between the REAT values and the BCLB method using noise bands.

The mean attenuation measurement differences (BCLB minus REAT) at the five frequencies are shown in Figure 3. For the pure tone BCLB, there was no clearly evident trend with frequency, although the largest mean difference was at the lowest frequency tested, which may indicate some influence of the occlusion effect. The occlusion effect was minimized by the constant presence of the headphones.

For the noise band BCLB procedure, the difference from the REAT results clearly was related to frequency with an approximately linear decrease in difference with increase in logarithm of the frequency. The closest agreement is at 2 kHz (at which point the loudness balance is done with equal frequencies). However, since attenuation also decreases with decreasing frequency, it is not clear whether the difference between the two procedures is affected by the attenuation value or the frequency decrease. The correlation coefficients for the attenuation difference were 0.686 with attenuation (REAT) and 0.575 with frequency.

Besides its comparability to REAT measurements, one of the questions about the BCLB procedure is the ability of the subjects to perform the loudness balance reliably relative to the consistency of performance on the REAT test. Since each threshold or balance determination was repeated under identical conditions with an interval of 5 min or less, the difference between the two determinations was a measure of the repeatability of the process. For both of the BCLB methods and the REAT procedure, most of the differences (>85%) were either 0 or 4 dB, since the possible changes in sound level were 4 dB steps. A measure of the difficulty of making a consistent response was the percentage of differences greater than 1 step (≥8 dB) which might be called errors. Table 2 shows the distribution of the errors between repeat tests for the three methods, subdivided by frequency and subject. The BCLB method using pure tones had a higher rate of errors (12.5%) than either of the other two methods (7.5% each), but the difference was not statistically significant ($p > 0.29$). There was also no clear indication of trend with frequency, although it is interesting to note that there were just as many errors at 250 Hz with each of the methods, even though the noise band BCLB test required comparison of loudness of very different sounds (2 kHz vs 250 Hz noise bands).

Another measure of the difficulty of the judgments of either loudness balance or threshold level was the time required for each test with all 5 frequencies. Table 3 shows the mean test times for each subject for each method. There was no significant difference between the times for the two BCLB methods or between the noise band BCLB test and the REAT test, but the pure tone BCLB mean test time was significantly less ($p < .01$) than the mean time for the threshold test. The times of subject 4 were also significantly longer ($p < .0005$) than the other 3 subjects for all methods, which may be related to the diminished variability of response for this subject (see Table 2). Also of interest when comparing Tables 2 and 3 is that all of the errors in the noise band BCLB test came from subject 2 who was also the only subject who took longer to do the noise band BCLB test than the threshold test.

All subjects reported that the pure tone BCLB test was the easiest to perform in that they could make quicker and more certain judgments about the loudness balance in that test than for either the threshold determination or the noise band loudness balance. The noise band BCLB test was reported to be the most difficult subjectively by 3 of the 4 subjects (subjects 2, 3, and 4) which could be related to the use of noise bands rather than pure tones or to the fact that bands of different frequencies were required to be matched. However, problems with deciding on the balance level were not reflected in either the test times or the repeatability of response, except possibly for subject 2.

Table 2 Assessment of Test Response Consistency

Percentage of Errors on Repeat Determinations[A]

Method	Subject				Frequency (Hz)					
	1	2	3	4	250	500	1k	2k	4k	All
BCLB (pure tones)	15	10	20	25	6	12.5	19	6	19	12.5
BCLB (noise bands)	0	30	0	0	6	6	12.5	0	12.5	7.5
REAT (pure tones)	10	5	15	0	6	6	6	12.5	6	7.5

[A] Errors are defined as determinations of loudness balance or threshold which differed by more than one sound level step (4 dB) for replicated tests less than 5 minutes apart. The percentage for each subject-method combination is based on 20 replications and for each frequency-method combination is based on 16 replications. Percentages are rounded to nearest 0.5.

Table 3 Loudness Balance or Threshold Determination Test Duration

Method	Mean Time[A] (seconds)				
	Subject				
	1	2	3	4	All
BCLB (pure tones)	112	144	120	203	145
BCLB (noise bands)	119	177	131	228	164
REAT (pure tones)	162	137	166	312	194
All methods	131	153	139	248	

[A] The time listed for each subject-method combination is the mean of 8 tests, each consisting of a loudness balance or threshold determination for 5 frequencies.

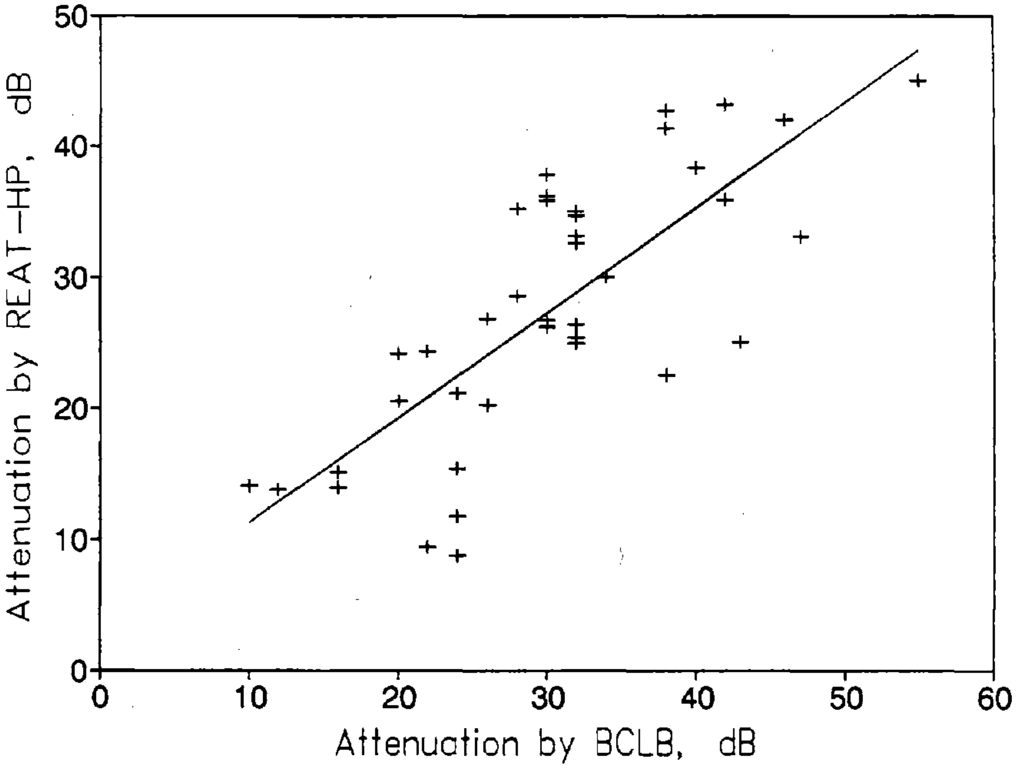

Figure 1. Hearing protector attenuation as measured by bone conduction loudness balance method with air conduction sound from headphones (BCLB) versus attenuation with the threshold difference method using headphones (REAT). The BCLB procedure used pure tone testing and equal air conduction and bone conduction frequencies. The solid line is the linear least-squares regression line for prediction of REAT from BCLB (REAT = 0.79BCLB + 3.5 dB).

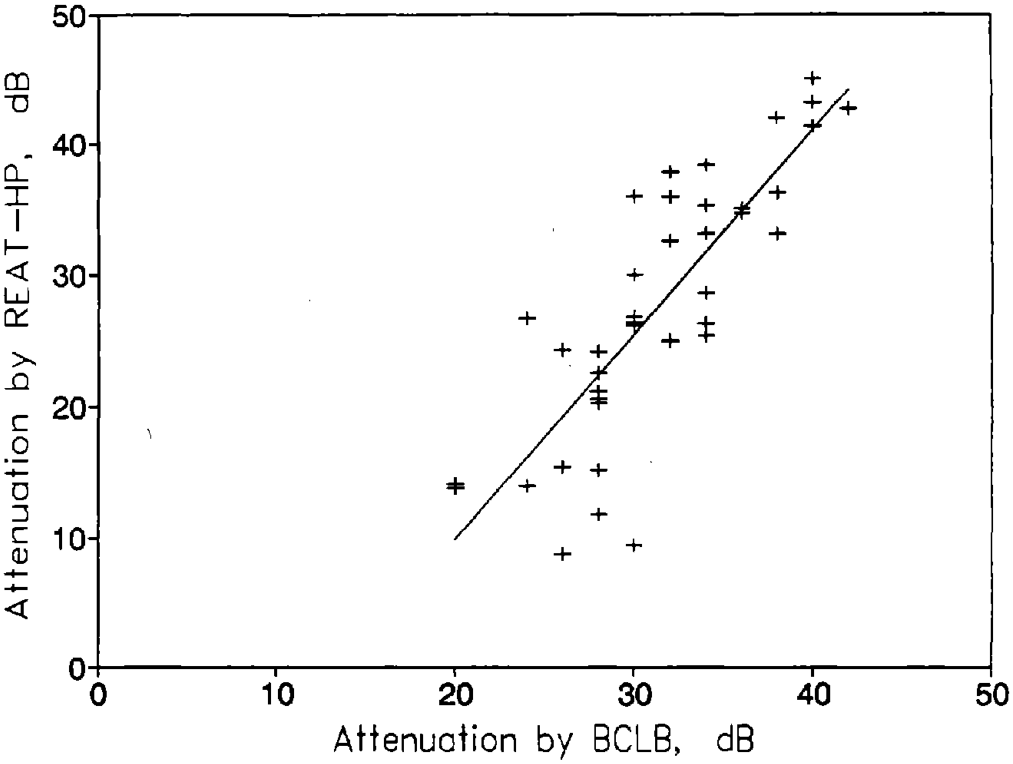

Figure 2. Hearing protector attenuation as measured by bone conduction loudness balance method with air conduction sound from headphones (BCLB) versus attenuation with the threshold difference method using headphones (REAT). The BCLB procedure used 1/3 octave bands of noise and a fixed bone conduction noise-band frequency of 2kHz; pure tone testing was done with equal air conduction and bone conduction frequencies. The solid line is the linear least-squares regression line for prediction of REAT from BCLB (REAT = 1.56*BCLB - 21.3 dB).

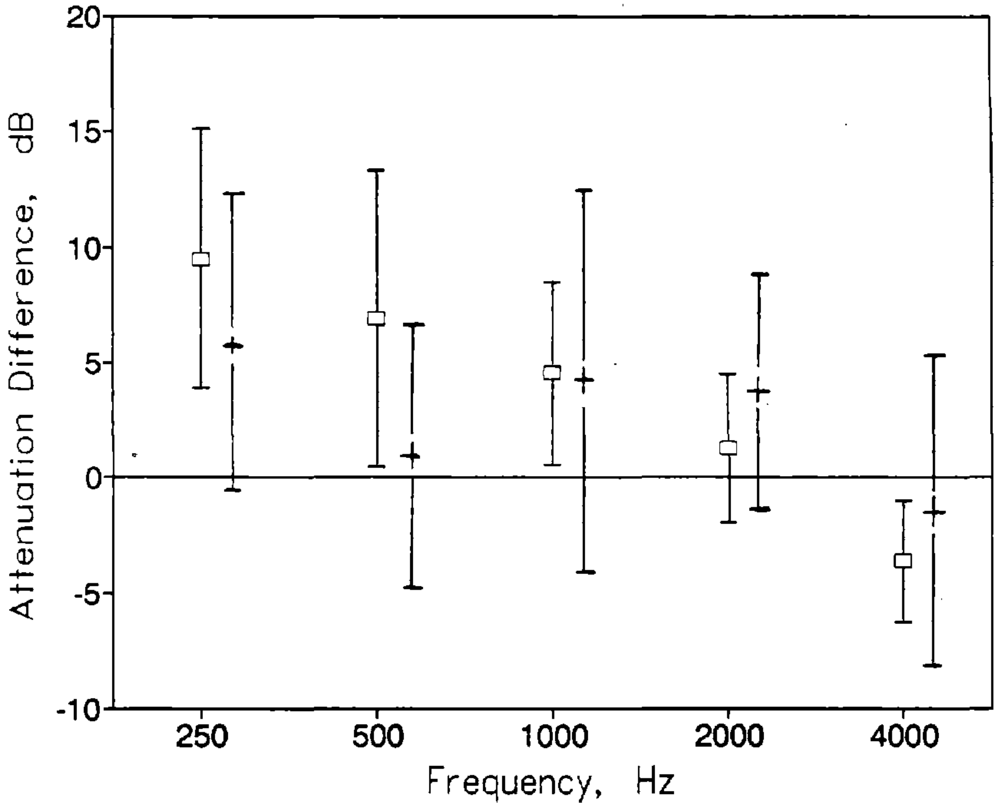

Figure 3. Mean difference in attenuation (BCLB minus REAT) versus center frequency of air conduction sound with bars for ± 2 standard errors. Noise-band BCLB (□); pure-tone BCLB (+)

EXPERIMENTAL PROCEDURE (PHASE 2)

This phase used a panel of 8 paid volunteers (4 women and 4 men) ranging in age from 18 y to 46 y. All subjects had normal hearing for speech, but one subject had a substantial hearing loss at 4000 and 8000 Hz, above the speech frequency range. None of the subjects was familiar with loudness balance testing prior to the testing.

For each subject, attenuation was measured for one HPD type (EAR Classic® slow-recovery foam earplugs) using both REAT and BCLB for two different fittings of the earplugs. In order to increase the range of attenuation values, the first fitting was done by the subjects with minimal training and the second with improved training and procedures. For the first fitting, attenuation was measured using REAT in minimum background noise conditions and BCLB in three background noise conditions (minimum and two elevated levels). For the second HPD fitting, only the minimum background noise environment was used for both the REAT and BCLB tests.

For both the REAT and BCLB procedures, the air conduction (AC) and bone conduction (BC) sounds were generated and controlled by a personal computer (Best 286®) with a digital-to-analog sound processor card (Soundblaster 16®). The test sounds (1/3 octave filtered bands of noise) were initially recorded from a compact disk source(19) as digital files (8 bits of resolution, sampling rate of 22 kHz). The digital sound data were then edited and stored as binary files using a format accessible by the sound processor.

For the BCLB procedure, the BC test signal was presented to the subject by a standard bone conduction vibrator (Radioear B-71®) placed on the forehead as in Phase 1B. The pressure of the vibrator against the forehead was not measured or standardized, but it remained constant during the series of tests for each subject.

All testing was conducted in a double walled audiometric test chamber, with interior dimensions 2.55 m wide by 2.75 m long by 2.0 m high (Industrial Acoustics Company). The AC sounds for both the REAT and BCLB procedures were generated from a pair of Klipsch Type HSM-BR® loudspeakers located 1.2 m front and back of the test subject centerline. The loudspeakers were driven by a 35 w amplifier (Realistic MPA-40®) receiving signals from the computer. Sound field uniformity tests measured around the subject's head location using 1/3 octave noise bands from 125 to 8000 Hz met the requirements of American National Standards Institute (ANSI) Standard S12.6-1984 (within a range of 6 dB in all locations and no more than 2 dB difference from left ear to right ear location)(20). The sound levels were calibrated over a range of about 80 dB from the maximum level attainable by the system (90 to 100 dB octave band levels, depending on the frequency) to the minimum measurable with the background noise. Linearity at all frequencies was within 0.5 dB at the head location, and the minimum step change in sound level was 2 dB.

The background noise in the test environment complied with ANSI Standard S12.6-1984 for accurate measurement of HPD attenuation with the REAT method, as shown in Table 4. BCLB measurements were also made in this low-noise environment as well as with higher background noise for evaluation of the procedure for field usage. The elevated background noise was generated from an additional pair of loudspeakers (Grason Stadler Model 162-4®) 1.1 m left and right of the subject centerline. The noise was provided by a recording of pink noise (random noise with equal sound pressure levels at each octave band) on an endless loop cassette tape and played with a tape recorder (Sony WM-D6C®) through an octave band graphic equalizer (Optimus Model 31-2030®) and amplifier (Sony CFS-1035®) and then into the speakers during the sessions requiring background noise. The graphic equalizer was used to control the levels of the octave band sound pressure levels to conform to the requirements for the specific background noise levels, as discussed below. The background noise was tested for uniformity in the same way as for the test signals and met the same requirements.

Two different elevated background noise levels were used, with the intention of representing (approximately) either the noise that would be expected in a typical industrial audiometric test booth or in an office setting where the BCLB test might be administered. For the industrial audiometric booth simulation, data were used from a 1994 study by Frank and Williams(21) of octave band levels in 490 different booths, all of which met background noise criteria set by the Occupational Safety and Health Administration).(18) The noise generation equipment was set to approximate the mean levels found in the audiometric booths, as shown in Table 4.

For the office noise simulation, standard architectural acoustics guidelines for heating, ventilating and air conditioning noise (Balanced

Noise Criteria Curves, NCB) were used to determine the octave band sound levels of the background noise expected for a situation (NCB-45) in which "fair listening conditions" are required, such as "lobbies, laboratory work spaces, drafting and engineering rooms, general secretarial areas".(22) Using the same procedure and equipment employed to simulate the audiometric booth background noise, pink noise was modified to approximate the octave band levels corresponding to NCB-45, as shown in Table 4.

A computer program, written in Microsoft QBasic® was used to control the test signals presented to the subject, to modify the sound level of the test signals in reaction to the subject responses, and to store the sound levels identified as thresholds or balance levels. The program used software provided with the sound processor as sub-routines to play the files and to control the sound level output. At the beginning of each test segment, the experimenter was prompted by the program to enter the subject identification number and the type of test conditions (REAT or BCLB, occluded or unoccluded ears, and level of background noise). The computer then automatically played the appropriate sound files through the digital-to-analog processor to produce the acoustical test signals, setting the initial sound level for the test signals as programmed for the type of test and then increasing or decreasing the AC sound pressure level in reaction to the subject responses. For each frequency, the computer then recorded the level at which the subject was able to achieve a consistent indication of either threshold or loudness balance determination, along with the number of trials necessary to achieve the consistent level.

For the BCLB tests, each presentation to a subject consisted of the following series of sounds: BC (0.5 s) - AC (0.5 s) - BC (0.5 s) - silence (1.0 s), repeated as often as needed. The period of silence was used to allow the subject to easily differentiate the sounds to be able to tell which was the fixed level sound (BC) and which was the sound that needed to be adjusted (AC) to match the loudness of the fixed level sound. The BC sound was always a 1/3 octave band noise at 2000 Hz center frequency at a constant level for each pair of BCLB measurements. Use of this BC sound was chosen on the basis of preliminary feasibility testing which showed that for sound field testing, the occlusion effect prevented the use of BC sounds below 2000 Hz for accurate attenuation determination. The level of the BC sound was found to be equivalent in loudness to about 35 dB (air conduction) for the two lower levels of background noise for this test panel. For the highest background noise condition, the BC sound level was increased 12 dB in order to be audible above the noise.

The AC sounds used in the BCLB testing were 1/3 octave bands of noise, with center frequencies of 8000, 4000, 2000, 500 and 125 Hz. The initial level of the AC sound at each frequency was set to a level that was well below the loudness of the BC sound, so the subject was required to initially approach the loudness balance "from below." The subject held a small plastic box with three pushbutton switches (labelled "+", "-", and "=") connected to the computer to allow control of the AC level. Each "+" button push increased the AC level by 4 dB until the subject decided that the AC sound was louder than the BC sound. The subject then decreased and increased the sound level (in 2 dB steps with each button push) as many times as desired until deciding that balance was reached, at which time the "=" button was pushed.

For the REAT tests, the same presentation and sound files as for the BCLB test were used, except that the BC sound was set to an inaudible level so that the subject heard only the AC sound (0.5 s) repeated once every 2 s. For each frequency, the AC sound started at a level approximately 40 dB above normal audiometric zero. The subject decreased the level in 4 dB steps for each push of the "-" button until the sound was inaudible. He or she then increased and decreased the level (in 2 dB steps with each button push) as many times as desired, until deciding that threshold was reached, at which time the "=" button was pushed.

In order to obtain reliable estimates of the threshold or balance levels, multiple responses within a pre-set range were required at each frequency before the subject could proceed to the next frequency for testing. The testing program was designed so that the value of the first AC level at which the subject indicated threshold or balance was temporarily stored in memory and the level was then changed by 12 dB (alternately either increased or decreased for BCLB; always increased for REAT). The 12 dB change was chosen to make a clear and distinct difference in loudness. The subject then varied the AC level until he again judged that threshold or balance had been achieved. If the second AC level was the same as for the first determination, its value was recorded and the program proceeded to the next frequency for testing. If the two values were different, the sound level was again changed by 12 dB, and the subject was required to again find and indicate the threshold or balance level. This value was compared to the first two levels and if it was within 2 dB of either one, an average value was computed, rounded to the nearest whole decibel and stored. (The computation of average sound level used all 3 values unless one was more than 2 dB from each of the others, in which case it was excluded). If, however, none of the 3 values was within 2 dB of any other, the AC level was again changed by 12 dB and the subject was again required to find the balance level. The process continued until any 2 of the most recent 3 levels agreed within 2 dB.

Each subject was tested individually in a single session using the following test sequence:

1. The subject was seated in the booth and asked to fasten the bone conduction transducer band around the head so the transducer made firm, but not uncomfortable contact with the forehead.
2. The subject was given the following instructions for the threshold test: "The goal of this test is to determine the lowest level of sound that you can hear. Press the minus (-) button until the pulsed sound can't be heard, then press the plus (+) button until it is just audible. Continue with minus (-) and plus (+) until you are confident that the sound is at the lowest level where it is still barely audible, then press the equal (=) button and wait for more sounds to be heard." The subject was then allowed to practice and demonstrate understanding of the threshold measurement.
3. The subject was then given the following instructions for the BCLB test: "The goal of this test is to make the sequence of three sounds as nearly equal in loudness as possible. To do this, increase or decrease the variable (middle) sound level as necessary with the plus (+) button and minus (-) button until you are confident that it is as close in loudness to the others as possible, then press the equal (=) button and wait for more sounds to be heard." The subject was then allowed to practice and demonstrate understanding of the BCLB measurement.
4. The experimenter then demonstrated compression and insertion of the foam earplugs (but without use of the normally recommended technique of pulling the outer ear to straighten the ear canal as the earplug is inserted). The subject then inserted both earplugs without assistance from the experimenter.
5. The experimenter left the booth, and the testing sequence began. For half of the subjects, the first test was threshold determination followed by BCLB in quiet (minimum background noise). For the other

half, the BCLB was first, followed by the threshold testing. For all subjects, the next two tests were loudness balance with low level background noise and then loudness balance with higher level background noise. For each of the 4 test sequences, the frequencies were presented in the order 8000, 4000, 2000, 500 and 125 Hz.

6. The subject was then asked to remove the earplugs and the 4 test sequences were repeated in the same order.
7. The experimenter then returned to the booth and demonstrated proper insertion of the earplugs, this time using the technique of pulling the outer ear to straighten the ear canal. The subject reinserted the earplugs using that technique with monitoring from the experimenter to achieve a visually good fit using several re-insertions if necessary.
8. The threshold determination and loudness balance in quiet were then repeated in the same order as for the initial tests.
9. After all testing was completed, the subject was interviewed for subjective impressions of the comparative difficulty of threshold determination versus loudness balance and of the effect of the background noise on the loudness balance process.

Attenuation was calculated for each fitting of the earplug separately at each frequency by subtracting the open-ear threshold or balance level from the occluded-ear threshold or balance level. Thus for the first fitting of the earplug, attenuation was calculated once by REAT and three times by BCLB (once for each background noise level). For the second fitting of the earplug, attenuation was calculated only once for REAT and once for BCLB, since elevated background noise was not used. For one subject, who had significant hearing loss at 4000 and 8000 Hz, the maximum level of AC sound (92 dB in those 1/3 octave bands) was not sufficient to achieve balance, so BCLB attenuation could not be calculated. Thus there were 38 values of attenuation by REAT [(5 frequencies x 7 subjects) + (3 frequencies x 1 subject)] for each of the two earplug fittings against which the BCLB attenuations could be compared.

RESULTS AND DISCUSSION (PHASE 2)

Figures 4-7 show the BCLB attenuation measured under various conditions plotted against the corresponding REAT values. Linear regression using least-squares fitting of an equation to predict REAT from BCLB gave the linear regression lines plotted as diagonals on Figures 4-7, with the 95% confidence bands for the regression lines also shown on the graphs. None of the regression lines was significantly different from the line for REAT = BCLB (at the 95% confidence level). Multiple linear regression using as additional variables the sound frequency, the logarithm of the sound frequency and an interaction variable of frequency x BCLB did not improve the fit of the equations.

For the low background noise condition, the mean values of attenuation at each frequency for the two procedures for each fitting of the HPD are shown in Figure 8 along with the manufacturer's mean attenuation data. Table 5 lists the mean and standard error of the differences at each frequency between the BCLB and REAT results for each background noise condition.

In addition to comparisons of the mean values of attenuation by BCLB and REAT, the individual pairs of values were examined to determine the distribution of differences between the BCLB and REAT methods. Table 5 shows that for the lower background noise conditions (21 dBA and 35 dBA), the distribution is fairly symmetrical with 65% of the pairs (74 of 114) being within 4 dB of each other and only 4 of the 114 pairs (3.5%) differing by more than 10 dB. For the high background noise (53 dBA), the distribution was clearly skewed away from zero, with 26% of the pairs (10 of 38) showing the BCLB attenuation measurement exceeding the REAT measurement by 10 dB or more.

Repeatability of the procedures was assessed in two ways, one of which was examination of the number of trials at each frequency that a subject required to reach a consistent threshold or balance level. The overall average number of trials was essentially equal for BCLB (2.61) and REAT (2.65), with the average number of trials showing a slight, but non-significant decline of about 5% as the testing proceeded for both REAT and BCLB. For both the REAT and BCLB tests, only 4% of the level determinations were sufficiently inconsistent that each of the first three trials differed by more than 2 dB from each other.

Another indication of the consistency of the balance procedure was the comparison between the balance levels achieved by each individual with the ears occluded in the two lower background noise conditions, which should have been equal since the BC signal was kept at the same level and the noise as attenuated by the HPD should not have been sufficient to have any influence. These pairs of balance levels had a mean difference of 0.3 dB, a standard deviation of 3.4 dB, and a correlation coefficient of 0.95.

The time required to make a consistent threshold or balance determination for each frequency was also used as an indication of the practicality of the BCLB method. The mean times were 87 s for REAT (standard deviation 11 s) and 76 s for BCLB (standard deviation 14 s), a difference that was not statistically significant ($p>0.05$). In general, the times decreased as the subjects gained experience with the tests, with the mean REAT time decreasing by 33% from the first test to the last and the mean BCLB time decreasing by 19%, again a difference that was not statistically significant ($p>0.05$).

When asked whether balance or threshold decisions were easier to make, 50% of the subjects chose balance, 25% chose threshold, and the remaining 25% said that they were about equal in difficulty. Also, 75% of the subjects stated that balance became more difficult with the highest level of background noise, but only one subject said that the background noise made balance "much harder." The background noise made no difference to 25% of the subjects.

The HPD attenuation measured with the BCLB procedure as tested in this study agreed well with attenuation as measured by the standard threshold difference method across the full span of frequencies normally tested (125 to 8000 Hz) for all except the highest background noise test environment. For the lowest background noise condition, only at 2000 Hz was there a significant difference, with BCLB mean results about 3 dB greater than REAT, a difference that was consistent within 0.1 dB over two separate sets of tests.

In addition to good agreement between BCLB and REAT for the mean attenuation at each frequency, the measurements by the two methods for each subject at each frequency agreed within 10 dB for 96.5% of the data pairs (over the two lower background noise conditions). This is important for predicting the usefulness of BCLB as a practical method for training and evaluation since the only other available study of a field attenuation procedure in which all of the data pairs were published showed much more frequent individual discrepancies greater than 10 dB when compared to REAT. This study, by Carter and Upfold in 1993,(23) compared REAT using headphones to the standard REAT sound field method for slow expansion foam earplugs and found 33 to 47% of paired attenuation values differing by more than 10 dB, depending on the headphone method used. Also, 11 to 14% differed by more than 20 dB. The authors concluded that the headphone REAT method could be used "to measure the overall, or group, effectiveness of the fitting and instructional procedures used", but that attenuation "in individual cases cannot be reliably estimated using a single test".

For the background noise condition equivalent to a typical industrial audiometric booth (35 dBA), the accuracy of the BCLB method was not significantly affected, although there was an definite trend toward an increase in the measured attenuation by BCLB as the background level increased. The highest background noise level, equivalent to a fairly noisy office (53 dBA), clearly appeared to affect the accuracy of the BCLB measurements relative to REAT, especially at 4000 Hz, and to a lesser degree at other frequencies. However, the lack of agreement between BCLB and REAT may have been an experimental artifact to some extent, since for the highest background level the BC signal was increased by 12 dB to overcome the masking effect of the noise. In principle, the subjects should have increased the AC level by 12 dB at each test frequency to compensate for the louder BC noise, but for the frequencies below 8000 Hz the level required to balance increased more than 12 dB (mean of 13.8 dB) with the open ears and less than 12 dB (mean of 8.4 dB) with the HPD in place, leading to a significant decrease in the BCLB attenuation measurement at 2000 and 4000 Hz. At 8000 Hz, the results showed very little increase in the air conduction balance level either for the open ear case (2.5 dB) or the occluded ear case (2.0 dB) compared to the expected 12 dB. Rather than being caused by the increased background noise, however, this unexpected result may be more attributable to either a non-linear loudness growth at the higher frequencies or to the subjects failing to make a shift in the accustomed balance level with the initial presentation (which in this experiment always occurred at 8000 Hz) at the higher BC level. A different experimental procedure in which the BC level was not changed during the course of the study would be more conclusive in regard to the higher level background noise effect. The actual results are nonetheless informative in that they point up possible difficulties in changing the BC level in the course of the measurements while still showing only a minimal interference by background noise at most of the frequencies.

Table 4 Octave Band Sound Pressure Levels for Background in Test Chamber

	Octave Band Center Frequencies (Hz)						
Condition	125	250	500	1000	2000	4000	8000
Measured (21 dBA)	27	18	9	10	7	8	10
Criteria[A]	28	18	14	14	8	9	20
Measured (35 dBA)	47	36	26	22	22	22	17
Criteria[B]	48	36	26	23	22	22	22
Measured (53 dBA)	58	54	50	47	45	41	33
Criteria[C]	58	53	50	47	43	40	37

[A] From ANSI 12.6-1984 - octave band levels low enough to avoid threshold elevation with the uncovered ear (21 dBA)

[B] Simulating background noise levels inside a typical industrial audiometric test booth (35 dBA)

[C] Simulating background noise levels in a moderately noisy office (53 dBA), as determined from Balanced Noise Criteria, NCB-45.

Table 5 Attenuation Differences for Various Background Noise Conditions

	1/3 Octave Band Center Frequencies (Hz)				
Condition	125	500	2000	4000	8000
Quiet, 21 dBA, 1st fit	0.0 (2.0)	1.3 (2.4)	3.1 (1.5)	-0.1 (1.4)	0.6 (1.1)
Quiet, 21 dBA, 2nd fit	0.5 (1.8)	-0.3 (1.6)	3.0 (1.1)	-0.1 (1.6)	0.6 (2.0)
Low noise, 35 dBA	-1.8 (1.6)	-1.0 (2.6)	0.6 (2.0)	-2.6 (1.1)	2.1 (0.9)
High noise, 53 dBA	-4.4 (3.5)	-2.8 (2.7)	-1.1 (2.5)	-9.8 (1.4)	2.0 (2.0)

Note: Attenuation difference is defined as BCLB result minus REAT result, in dB. Figures in table are the mean and (standard error) in dB.

Table 6 Distribution of Attenuation Differences by Background Noise Conditions

	BCLB - REAT, dB				
Condition	< -10	-10 to -5	-4 to 4	5 to 10	>10
Quiet, 21 dBA, 1st fit	0	4	25	8	1
Quiet, 21 dBA, 2nd fit	0	5	25	7	1
Low noise, 35 dBA	1	8	24	4	1
High noise, 53 dBA	10	6	15	7	0

Note: Attenuation difference is defined as BCLB result minus REAT result, in dB. The numbers in the table are the numbers of pairs of values differing by the specified amount for each background noise condition.

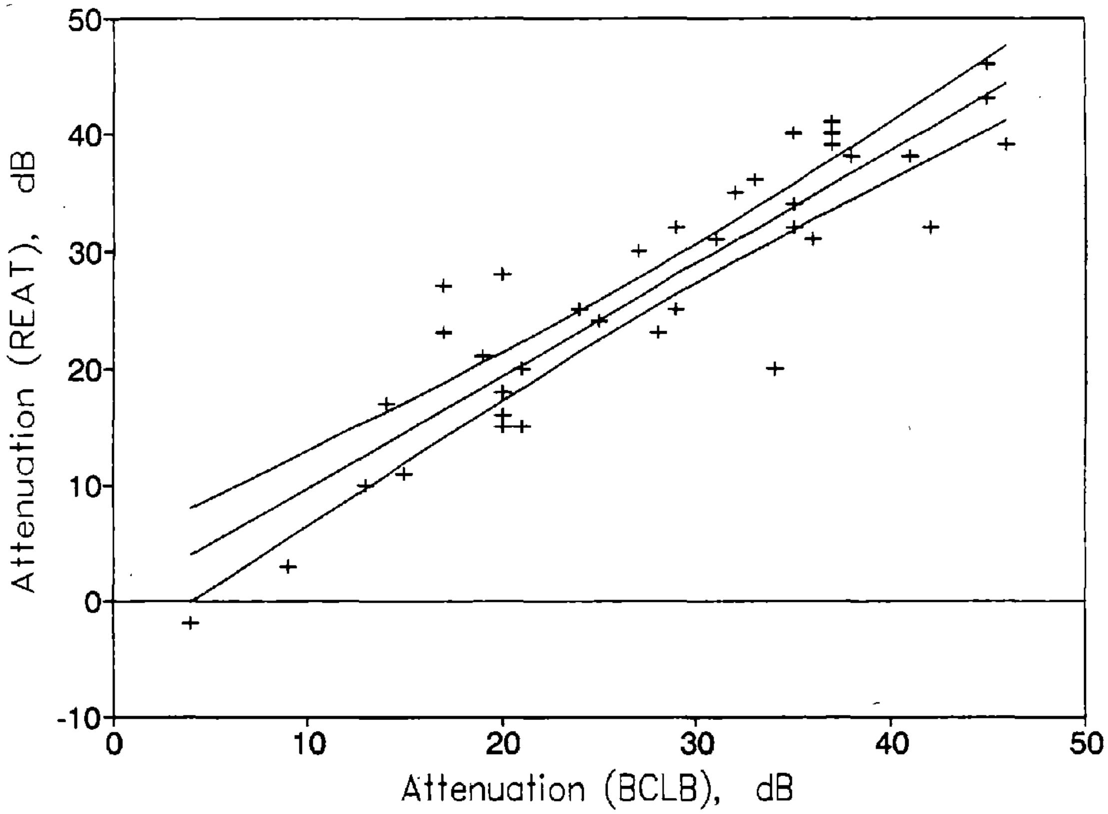

Figure 4. Attenuation as measured by bone conduction loudness balance (BCLB) and real ear attenuation at threshold (REAT) for the first HPD fit with "quiet" background noise (21 dBA). Each point represents one of the eight subjects and one of the five frequencies tested (125 to 8000 Hz). The diagonal lines are the least-squares regression line and the 95% confidence limits for the regression line. The Pearson correlation coefficient is 0.90.

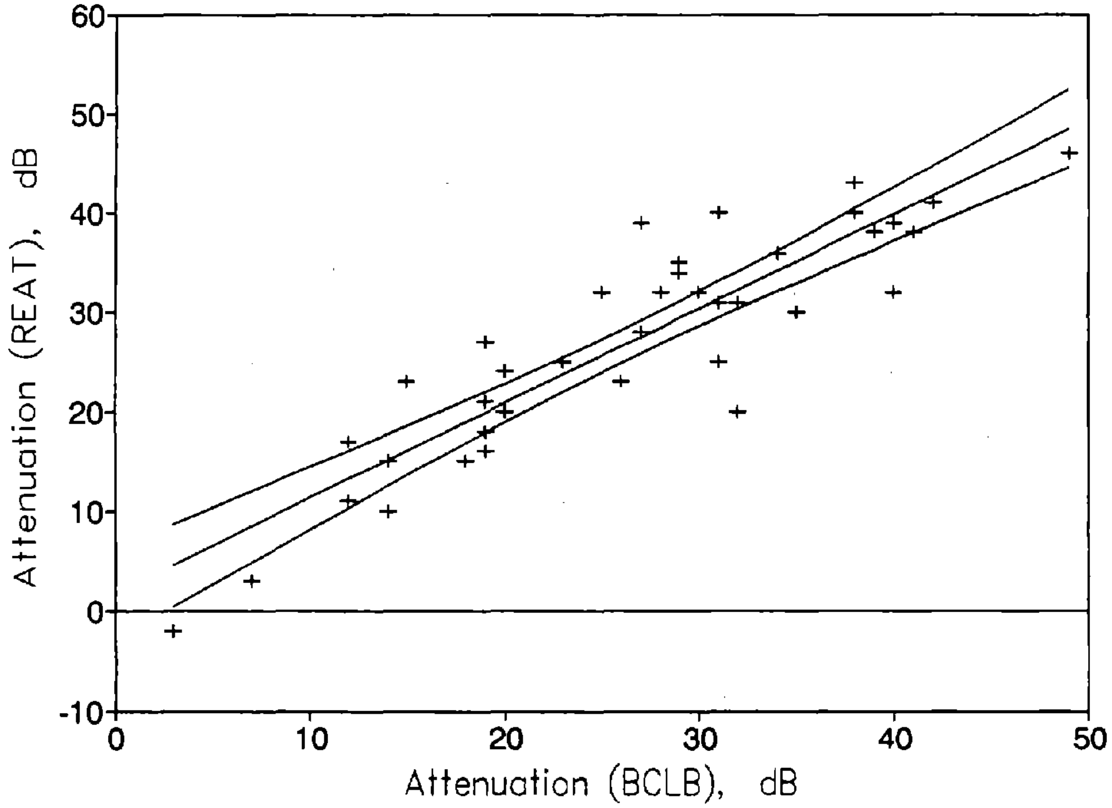

Figure 5. Same as Figure 4 except that the background noise was at a level and frequency distribution intended to represent a typical industrial audiometric test environment (35 dBA). The Pearson correlation coefficient is 0.90.

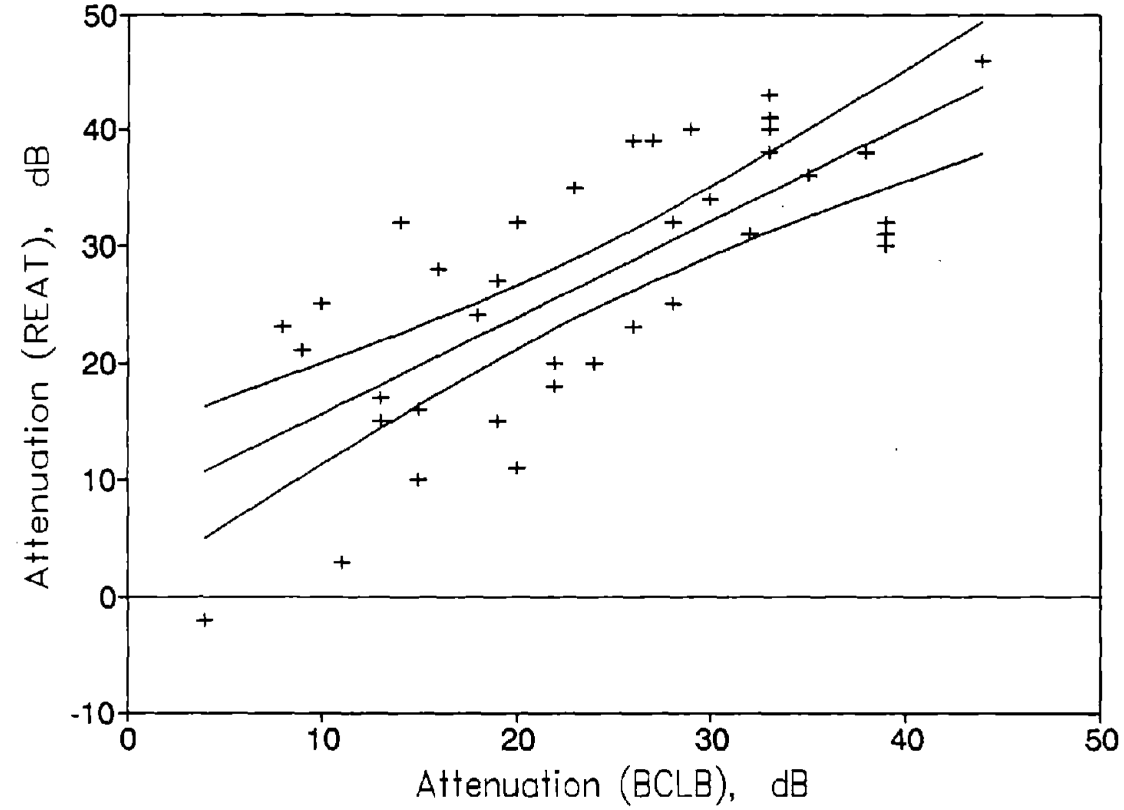

Figure 6. Same as Figure 4 except that the background noise was at a level and frequency distribution intended to represent a fairly noisy office environment (53 dBA). The Pearson correlation coefficient is 0.74.

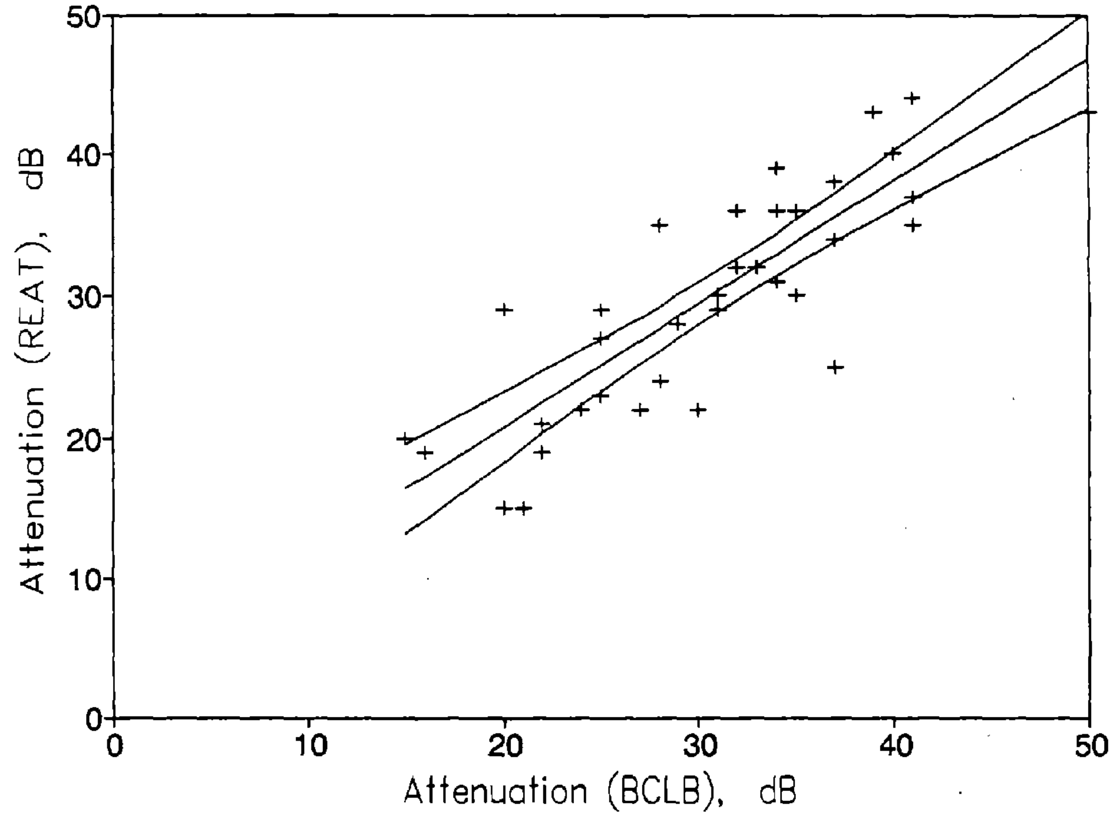

Figure 7. Same as Figure 4 except that the data are for the second, improved fit of the HPD in which the ear canal was straightened prior to earplug insertion. The Pearson correlation coefficient is 0.86.

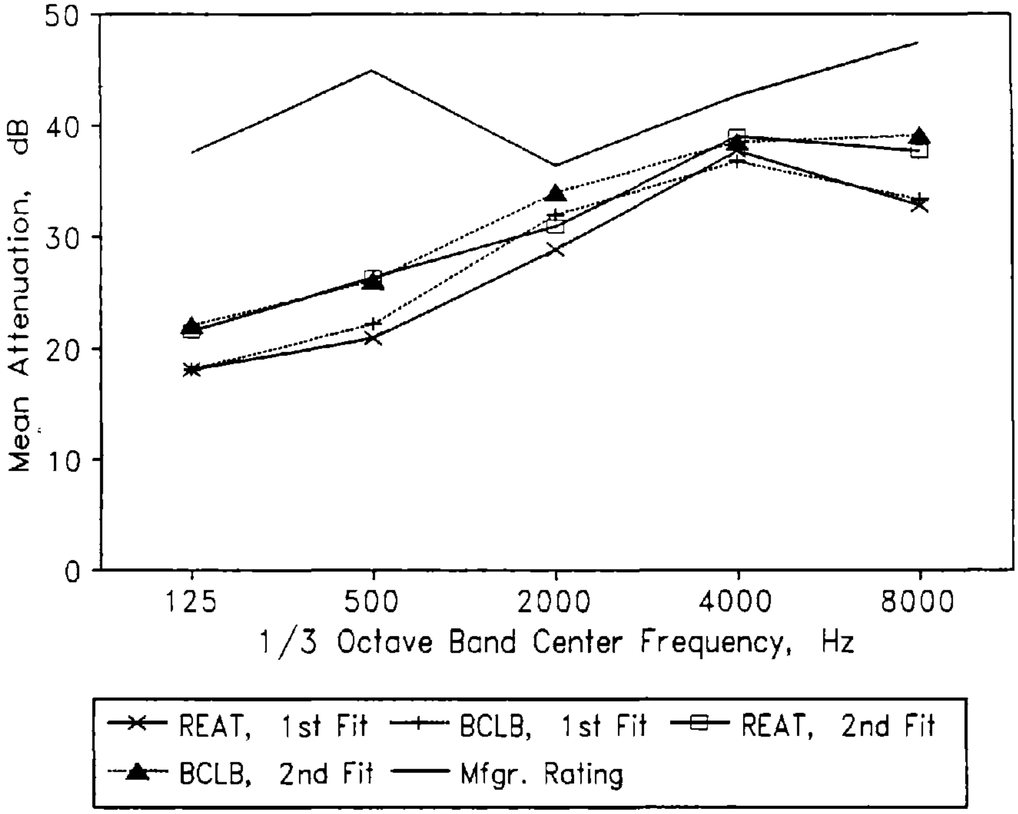

Figure 8. Mean attenuation measured by BCLB and REAT for the first HPD fit and for the second, improved HPD fit, both with the lowest background noise conditions along with the mean attenuation reported for the same earplug by the manufacturer.

EXPERIMENTAL PROCEDURES (PHASE 3)

The objectives of this phase of the study were: (1) to compare attenuation as measured by BCLB to attenuation as measured by the standard REAT procedure for representative examples of each of the major HPD types, (2) to make the comparison for all nine of the standard test frequencies, (3) to compare REAT and BCLB results for A-weighted attenuation of typical industrial noises by combining the individual frequency results, and (4) to simplify and standardize the testing procedure by improving the testing protocol which was used during the previous evaluations.

This study phase used a panel of 24 paid volunteers (17 women, median age 23 y, and 7 men, median age 31 y) who were not screened for hearing ability prior to their participation. None wore HPDs at work, although several occasionally used them for target shooting.

Three different HPDs, selected to be representative of their types, were used: expandable, slow-recovery foam earplugs (EAR Classic®), earmuffs (Bilsom Viking 29®), and canal caps (Caboflex® Model 600). Also, the combination of the earplugs and earmuffs was tested. Most subjects wore three of the four HPDs, but for reasons of time limitation or fatigue three subjects wore fewer. The earplugs were tested for 22 subjects, earmuffs for 19, earmuffs and earplugs combined for 19, and canal caps for 12. For the earmuffs (worn with headband over the head) and canal caps (headband under the chin), the subjects were not given any fitting instructions other than to adjust the HPD so that it was comfortable and felt secure and to remove earrings, eyeglasses, or hair that would be under the sealing surface of the earmuff cups. For the earplugs, the manufacturer's recommended process of compression and insertion of the earplug using the technique of pulling the outer ear to straighten the ear canal was demonstrated. The actual insertion was done by the subjects without assistance, but re-insertion was encouraged if the subject thought that an earplug did not fit well or if it appeared to the experimenter to be loose. No more than one re-insertion was done by any subject, although it was visually evident that many subjects did not achieve a deep insertion. Relatively poor fitting of the earplugs was allowed since the experimental objective was validation of a field test method suitable for normal HPD use in which many earplug wearers would be expected to achieve a less-than-optimum fit.

The order of testing HPDs was randomly varied so that each HPD had an equal number of tests in each position in the sequence. For the combination of earmuffs and earplugs, the same fitting of the earplug was used in both tests so that no re-insertion of the plugs would be required.

The equipment, procedures, and test environment were generally the same as in Phase 2, with a few exceptions. The computer program was modified to accommodate changes made in the presentation of the sounds, the additional frequencies to be tested, and differences in the criteria for establishing consistency in BCLB levels. The BC sound was the same as in Phase 2 (a 1/3 octave band noise at 2000 Hz center frequency) and was set to a level equivalent in loudness to about 35 dB (air conduction) for subjects with normal hearing, but for subjects who could not hear the BC sound clearly during the instructional phase of the testing, the level was increased 12 to 20 dB, as needed. Once set at a comfortably audible level, the BC sound level was maintained at a constant level for each subject. The AC sounds were 1/3 octave bands of noise, with center frequencies of 8000, 6300, 4000, 3150, 2000, 1000, 500, 250, and 125 Hz. The initial level of the AC sound at each frequency was set at a level that was well below the loudness of the BC sound, so the subject was instructed to increase the AC sound level by pushing the "+" button (4 dB per step) until she judged that the AC sound was louder than the BC sound. The subject then decreased the AC sound level (in 2 dB steps with each button push) until the AC and BC sounds were equally loud, at which time the "=" button was pushed. The AC sound was then automatically decreased by 12 dB, and the subject repeated the same process of loudness balance. Once a consistent balance level was established for each frequency, the AC sound for the next frequency was started, always beginning lower than the BC loudness. This procedure was a simplification of that used in the previous phase in that the subject was discouraged from "hunting" up and down to make the balance decision. Another modification (also made to simplify and speed the loudness balance process) was that the AC sound level was always decreased 12 dB after balance was indicated, rather than being alternately increased and decreased.

For the REAT tests, the same presentation and same 1/3 octave band AC sounds as for the BCLB test were used but with sound files containing only the AC sound (0.5 s) repeated once per second. For each frequency, the AC sound level started at a level approximately 40 dB above the normal threshold of hearing for testing with "open" ears (no HPD in use). For testing with HPDs present, the initial level was set 28 dB higher at each frequency than for the open ear condition. The subject decreased the level in 4 dB steps for each push of the "-" button until the AC sound was inaudible. She then increased the sound level (in 2 dB steps with each button push) until the sound became "barely" audible, at which time the "=" button was pushed. The sound level was then automatically increased 12 dB and the subject repeated the same process of threshold determination until achieving a specified degree of consistency. When a consistent threshold level was reached, sound at the next frequency was presented, again starting well above threshold and the pattern was repeated.

As in Phase 2, multiple responses for either loudness balance or threshold within a pre-set range of sound levels were required at each frequency before the subject could proceed to the next frequency for testing. For REAT testing, the requirements were the same as before (either the first two responses had to be at the same level or any two of the most recent three responses had to agree within 2 dB). For BCLB, any two of the most recent three responses had to agree within 2 dB, a more lenient criterion than in the previous study intended to speed testing. When the subject met the consistency requirements for a particular frequency, an average value for either threshold or balance level was computed, rounded to the nearest whole decibel and stored. The computation of average sound level used all three of the most recent values unless one was more than 2 dB from each of the others, in which case it was excluded. If more than three trials were required to meet the consistency requirements, the responses prior to the final three were excluded from any computations.

Each subject was tested individually in a single session lasting from 1.5 to 2 h using the following test sequence:

1. The subject was seated in the booth and asked to fasten the bone conduction transducer band around the head so the transducer made "firm, but not uncomfortable," contact with the forehead.
2. The subject was given the following written and oral instructions for the REAT test: "The goal of this test is to determine the lowest level of sound that you can hear. Press the minus (-) button until the pulsed sound can't be heard, then press and quickly release the plus (+) button as many times as necessary until the sound is just barely audible. Then press the equal (=) button and wait for more sounds to be heard." The subject was then allowed to practice and demonstrate understanding of the threshold measurement.
3. The subject was then given the following written and oral instructions for the BCLB test: "The goal of this test is to make the sequence of three sounds as nearly equal in loudness as possible. To do this, increase the variable (middle) sound level with the plus (+) button until it is louder than the first and third sounds. Then press and quickly release the minus (-) button until it is as close in loudness to the others as possible, then press the equal (=) button and wait for more sounds to be heard." The subject was then allowed to practice and demonstrate understanding of the BCLB measurement.
4. The experimenter then demonstrated whichever HPD was to be tested first and the subject donned the HPD. The experimenter left the booth, and the testing sequence began. For half of the subjects, the first test was

threshold determination followed by BCLB; for the other half, BCLB was first, followed by the threshold testing. In each case, all nine frequencies (in order from highest to lowest frequency) were tested for each procedure and then all nine were done in the same order for the next procedure.

5. After threshold and BCLB levels were established for the first HPD at all frequencies, the experimenter then demonstrated whichever HPD was to be tested next, the subject donned the HPD, and the testing sequence was repeated in the same order as for the first HPD. This process continued until all HPDs for that subject had been tested. After either the first or second HPD was tested, the threshold and BCLB tests were done with no HPD in place. The subject was given a 10 min rest break in the middle of the testing process.

6. After all testing was completed, the subject was interviewed for subjective impressions of the comparative difficulty of threshold determination versus loudness balance.

Attenuation was calculated for each HPD separately at each frequency by subtracting the open ear threshold or balance level (measured once at each frequency for each subject) from the occluded ear threshold or balance level (as measured at each frequency for each HPD for the subject). Thus there were 198 values of attenuation by REAT (9 frequencies x 22 subjects) for the earplugs against which the BCLB attenuations could be compared. For the other HPDs, the total number of comparisons were 171 (earmuffs), 171 (earmuffs and earplugs combined), and 108 (canal caps).

In addition to the attenuation comparisons at each frequency, the overall reduction in A-weighted sound level was calculated for each combination of HPD, subject, and method. Since the A-weighted sound reduction depends on the frequency distribution of the sound that the HPD is protecting against, three different exposure spectra were used as representative types of possible real-world conditions. These conditions were: flat noise spectrum (all octave bands equal), high frequency noise spectrum (intensity increasing by 4 dB/octave) and low frequency noise spectrum (intensity decreasing by 8 dB/octave). These different spectra are representative of the range of actual noise conditions that might be encountered on the job.(24) For each spectrum, the HPD attenuation was subtracted from the appropriate octave band level, A-weighting was applied, the resulting octave band levels were summed, and the total was subtracted from the original (unattenuated) A-weighted level for that spectrum. An example of the calculation for the flat noise spectrum is shown in Table 7.

RESULTS AND DISCUSSION (PHASE 3)

Figures 9 - 12 show the measured BCLB attenuation for the four different HPD configurations plotted against the corresponding REAT values. For each graph, the least-squares linear regression line and its 95% confidence bands are also plotted. The coefficients for the linear regression are listed in Table 8. Simple linear regression using only the BCLB measurement as an independent variable explained 58% to 73% of the variation in REAT, as measured by adjusted R^2 when the different HPD types are considered separately, but improved to 80% when the equation was calculated using all HPD types together, yielding the equation:

$$REAT = 0.98*BCLB + 0.9$$

in which the BCLB coefficient was not significantly different from 1 and the constant was not significantly different from 0.

Multiple linear regression analysis was carried out using additional variables along with the BCLB result to better predict the REAT value for each HPD type. The variables used were various combinations of sound frequency, the order of presentation, the subject gender, the subject's preference for REAT or BCLB, the logarithm of frequency and an interaction variable of log frequency*BCLB. Only the latter two independent variables noticeably improved the equation fit for earmuffs (R^2 increased from 0.58 to 0.71) and for earplugs and earmuffs combined (R^2 increased from 0.63 to 0.70). There was no useful improvement in the equation fit for earplugs or canal caps or for the equation with all HPD types together, for which the R^2 value was not increased by any combination of additional variables. (These multiple regression coefficients are listed in Table 9).

When HPD type was also included as a variable, the best equation fit ($R^2 = 0.83$) was achieved using three dummy variables for the four HPD types along with the BCLB value and the sound frequency as the other independent variables. The regression coefficients and their standard errors are given in Table 10, and the predictive equations for the different HPD types are as follows:

REAT = 0.81*BCLB + 0.00047*frequency + 5.7 dB [earplugs]
REAT = 0.81*BCLB + 0.00047*frequency + 2.9 dB [earmuffs]
REAT = 0.81*BCLB + 0.00047*frequency - 1.0 dB [canal caps]
REAT = 0.81*BCLB + 0.00047*frequency + 7.6 dB [earplugs & earmuffs]

These equations indicate that the increase in attenuation by REAT increases only about 80% as rapidly as the increase as measured by BCLB and that the effect of frequency on the prediction is minor, amounting to only about

3.5 dB over the full range from 125 Hz to 8000 Hz. The constant factor for HPD type varies over a range of 8.6 dB with a decrease in REAT predicted from the BCLB factor for the HPD type with the least attenuation (canal caps) and an increase in the predicted REAT from the BCLB factor which progressively increases as the overall HPD performance increases (from earmuffs to earplugs to earplugs combined with earmuffs).

Linear regression analysis was also used to examine the subject-by-subject relationship between REAT and BCLB results and to be able to assess the degree of variability among subjects. The means and standard errors of the regression coefficients are listed in Table 11, and a histogram of the regression slope distribution among subjects for each HPD type is shown in Figure 13.

Overall, the Pearson correlation coefficient between REAT and BCLB attenuation was 0.89, with the following breakdown by HPD type: earplugs, 0.86; earmuffs, 0.76; canal caps, 0.86; earplugs and earmuffs combined, 0.80. In Figures 14 - 17, the mean attenuation at each frequency as measured by BCLB and REAT are plotted for each HPD, along with the mean attenuation value provided by the HPD manufacturer as based on laboratory certification tests. (For the case of the earplug and earmuff combined, there is no manufacturer's data).

The A-weighted attenuations by REAT and BCLB for each subject and HPD combination are displayed in Figures 18 - 20 for the three different noise exposure conditions (flat spectrum, high frequency, and low frequency). The mean A-weighted attenuations calculated by the different methods are listed in Table 12 by HPD type and noise spectrum.

The difference between each pair of BCLB and REAT measurements was computed and the mean differences and standard error of the means are shown in Table 13 by HPD type and sound frequency. The individual pairs of attenuation values were also examined to determine the distribution of differences between the methods. The cumulative distributions of differences for each HPD type are plotted in Figure 21, which clearly shows that the distribution for the canal caps was offset from those of the other HPD types which were almost coincident.

Another way to analyze the difference data is shown in Tables 14 and 15 which list the percentage of data pairs for each subject showing either good agreement (difference arbitrarily defined as less than 5 dB) or poor agreement (difference arbitrarily defined as greater than 10 dB). The same information is presented in graphical form as histograms in Figures 22 and 23 to better display the distribution of differences in data pairs among subjects. Table 14 shows that the overall mean percentage of data pairs with good agreement was 55%, with a range of means for the different HPD types from 53 to 56%. Table 15 shows that the overall mean percentage of data pairs with poor agreement was 9%, with a range of means for the different HPD types from 8 to 11%. In both tables, it is noticeable that one subject (#9) had a much higher percentage of poorly agreeing data pairs (56%) than the mean and a much lower percentage of data pairs in good agreement (15%) than that mean. This subject was otherwise unremarkable in terms of age, hearing ability or repeatability of measurements. Analyzed without this subject, the percentage of poorly agreeing data pairs decreases from 9% to 7% for all HPD types and from 9% to 5% for earplugs.

To determine if subjects having relatively good or relatively poor agreement between attenuation measurements with one HPD type also showed relatively good or poor agreement for other HPD types, Pearson correlation coefficients were computed from the data in Tables 14 and 15 for each pair of HPD types and are displayed in Table 16 and 17. Again the data were analyzed both with and without subject 9 to show the effect of this outlier data.

Repeatability was assessed by examination of the number of trials at each frequency required by each subject to reach a consistent threshold or balance level. For both the REAT and BCLB tests, only 1% to 2% of the level determinations for all HPD types were sufficiently inconsistent to cause each of the first three trials to differ by more than 2 dB. Table 18 shows the distribution of differences between trials, indicating a very slight superiority of REAT to BCLB in this regard, but it was not a statistically significant difference ($p>0.50$, X^2 test). Only minor variations from the mean are seen when repeatability is analyzed for the different HPD types, as seen in Table 18.

The times required for determining the threshold or balance level for all nine frequencies for a particular method and HPD were also evaluated as an indication of the practicality of the BCLB method. The mean times were 508 s for REAT (standard deviation 198 s) and 549 s for BCLB (standard deviation 151 s), a difference that was not statistically significant ($p>0.10$).

When asked whether balance or threshold decisions were easier, 50% of the subjects chose threshold, 37.5% chose balance, and the remaining 12.5% said that they were about equal in difficulty.

As in the previous phase of the study, attenuation as measured by BCLB agreed well with REAT for earplugs at most frequencies, although there were some differences between the two phases noted at individual frequencies. Specifically, Phase 2 showed a statistically significant BCLB-REAT difference only at 2000 Hz, whereas the second phase showed a significant underestimate of attenuation at the higher frequencies from 3150 through 6300 Hz. For the earmuffs and the combination of earmuffs and earplugs, differences at only one and two frequencies, respectively, differed significantly from 0, and these were all underestimates of attenuation as measured by REAT.

For canal caps, however, there was a clear trend for BCLB to measure higher attenuation than REAT across all frequencies, with five of the nine differences being statistically significant. Since this trend was not noted for the other HPDs, a likely explanation is that the canal caps caused a small occlusion effect at 2000 Hz. (The occlusion effect is the increase in sensitivity of the ear to bone conducted sound when the outer ear is closed). With the HPD in place, the BC sound would thus be louder than with open ears, thereby requiring a corresponding increase in the air conduction sound to balance, spuriously elevating the calculated attenuation. The occlusion effect is normally considered to be negligible at 2000 Hz, which is the reason that that frequency was chosen for the BC sound in BCLB testing, but canal caps have been shown to have an enhanced occlusion effect compared to other HPDs,(14) though not necessarily at 2000 Hz. For the particular type of canal cap used in this work, an occlusion effect of only 3 dB would explain the results.

Regression analysis of the prediction of REAT attenuation by BCLB attenuation showed that a simple equation using only the BCLB value accounted for 80 percent of the variation in the REAT value, and that the addition of variables for frequency and HPD type increased the R^2 value to 83%. However, use of this sort of analysis may be questioned, since it relies on the assumption of independent observations when in actuality the 648 data points were acquired by testing only 24 subjects. Each of the data points was a unique combination of subject, HPD type and frequency, but there may be some correlation within each subject which causes a loss of independence between the individual observations. If that were the case, the regression analysis subject-by-subject might be expected to yield mean R^2 values higher than when all subjects are considered together, but comparison of Tables 8 and 11 does not show that to be the case. Also, high within-subject correlation might have been expected to cause subjects with either particularly good or particularly poor attenuation agreement for one HPD type to have that same sort of agreement for other HPD types, but the correlation coefficients in Tables 16 and 17 are quite low.

Although some loss of independence of the various data points cannot be ruled out, it does not appear to have had a large effect on the analysis.

Examination of the data in Figures 10 and 11 shows some of the attenuation values as measured by either REAT or BCLB or by both procedures to be less than zero, meaning that the presence of the HPD apparently caused the test sound to be louder than it was without the HPD. Each of these situations occurred at the two lowest frequencies (125 and 250 Hz) and may have been attributable either to a resonance effect in which the HPD caused amplification of the incident sound or to the random variation in the measurement of loudness balance and threshold.

The changes made to shorten the time required for the testing process by simplifying the balance and threshold procedures and relaxing the consistency criteria for balance appear to have had the desired effect. Compared to the previous phase of the study, the mean time required to determine the threshold or balance level for each frequency declined from 88 s to 56 s (threshold) and from 76 to 61 s (BCLB). This change was accomplished without any substantial decline in repeatability, at least as evidenced by the very small fraction of trials in which more than three trials were required to attain agreement within 2 dB.

The BCLB procedure as tested in this phase of the study appeared to reasonably predict attenuation as measured by the standard method, REAT, for all frequencies normally tested (125 to 8000 Hz). Despite the attenuation differences at individual frequencies seen for earplugs, earmuffs, and earmuffs/earplugs combined, the A-weighted attenuation for broad-band noise showed good agreement between methods regardless of the type of noise spectrum to be protected against. In particular, excellent correspondence (within 1 dB) was found between the methods for the earplugs and for the combination of earplugs and earmuffs. Slightly poorer agreement between methods was found for earmuffs, but only for canal caps was the difference in procedures statistically significant, with the BCLB method tending to give results for A-weighted attenuation that were 3 to 4 dB higher than were measured by REAT.

Table 7 Example Calculation for A-weighted Attenuation (Flat Noise Spectrum)

	1/3 Octave Band Center Frequencies (Hz)								
	125	250	500	1000	2000	3150	4000	6300	8000
Assumed exposure	100	100	100	100	100	100	100	100	100
A-weighting factors	-16	-9	-3	0	+1	+1	+1	0	-1
Exposure (A-weighted)	84	91	97	100	101	101	101	100	99
Measured attenuation	15	16	20	25	33	36	36	35	33
Protected level	69	75	77	75	68	65	65	65	66

Exposure level (A-weighted) = 109 dBA
Protected level (A-weighted) = 82 dBA
A-weighted attenuation = 27 dB

[A] For clarity in this table, A-weighting factors are shown rounded to the nearest whole dB, but in actual calculations, the nearest 0.1 dB was used.

Table 8 Coefficients for Linear Regression Analysis for Prediction of REAT Attenuation from BCLB Attenuation

HPD Type	Slope	Intercept	Adjusted R^2
Earplugs	0.94 (0.04)	-3.0 (1.4)	0.73
Earmuffs	0.85 (0.06)	3.5 (1.2)	0.58
Canal caps	0.90 (0.05)	-1.2 (1.1)	0.74
Earmuffs/earplugs combined	0.78 (0.05)	10.2 (1.8)	0.63
All HPD types	0.98 (0.02)	0.9 (0.6)	0.80

Note: Figures in parentheses are standard errors for the regression coefficients directly above.

Table 9 Coefficients for Multiple Linear Regression Analysis for Prediction of REAT Using the Equation REAT = a*BCLB + b*(log frequency) + c*(log frequency*BCLB) + d

HPD Type	a	b	c	d	Adjusted R^2
Earplugs	0.87	1.0	-	-2.1	0.74
	(0.05)	(0.4)	-	(2.1)	
Earmuffs	1.25	5.2	-0.1	-25.1	0.71
	(0.26)	(0.7)	(0.04)	(4.6)	
Canal caps	0.79	1.3	-	-8.8	0.76
	(0.06)	(0.4)	-	(2.7)	
Earmuffs/earplugs	1.72	7.6	-0.2	-34.2	0.70
combined	(0.26)	(0.7)	(0.04)	(4.6)	
All	1.15	1.6	-0.03	-9.0	0.80
	(0.10)	(0.4)	(0.01)	(2.7)	

Note: Use of the "c" coefficient did not improve the equation fit for the earplugs and canal caps, so it was omitted from the table.

Table 10 Coefficients for Multiple Linear Regression Analysis for Prediction of REAT Using BCLB, Frequency, and HPD Type as Independent Variables for the Equation REAT = a*BCLB + b*frequency + c*H1 + d*H2 + e*H3 + f

Coefficient	Value	Standard Error	P-value
a	0.81	0.026	<0.0005
b	0.00047	0.000095	<0.0005
c	-2.8	0.68	0.003
d	-6.7	0.78	<0.0005
e	1.9	0.64	<0.0005
f	5.7	0.86	<0.0005

Adjusted $R^2 = 0.83$

Note: For earplugs, H1=H2=H3=0; for earmuffs, H1=1 and H2=H3=0; for canal caps, H2=1 and H1=H3=0; for earplugs and earmuffs combined, H3=1 and H1=H2=0.

Table 11 Mean Values of Coefficients and R^2 for Linear Regression Analysis for Prediction of REAT Attenuation from BCLB Attenuation Separately for Each Subject

HPD Type	Slope	Intercept	Adjusted R^2
Earplugs	0.81	8.0	0.55
	(0.08)	(3.1)	(0.06)
Earmuffs	0.95	1.6	0.64
	(0.06)	(1.6)	(0.05)
Canal caps	0.92	-1.7	0.73
	(0.07)	(1.6)	(0.06)
Earmuffs/earplugs combined	0.86	7.4	0.61
	(0.08)	(3.0)	(0.07)
All HPD types	0.97	1.71	0.76
	(0.03)	(1.2)	(0.04)

Note: Figures in parentheses are standard errors for the mean values directly above.

Table 12 A-weighted Mean Attenuation by HPD Type and Measurement Method for Different Noise Spectra[A]

HPD Type	Flat	Low Frequency	High Frequency
Earplugs			
Mean (BCLB)	30.7	24.0	34.2
Mean (REAT)	31.2	24.1	35.3
Difference	-0.5	-0.1	-1.1
Std. Error	1.0	0.9	0.9
Earmuffs			
Mean (BCLB)	19.6	7.9	22.5
Mean (REAT)	19.6	5.1	24.4
Difference	0.0	2.8	-1.9
Std. Error	1.2	1.7	0.8
Canal caps			
Mean (BCLB)	17.0	8.9	20.5
Mean (REAT)	13.3	5.3	17.4
Difference	3.7*	3.6*	3.1*
Std. Error	1.2	1.5	0.8
Plug + muff			
Mean (BCLB)	37.7	26.1	40.9
Mean (REAT)	38.8	26.4	42.0
Difference	-1.1	-0.3	-1.1
Std. Error	1.0	1.2	1.1

[A] Noise spectra are defined as follows: flat - equal octave band sound pressure levels; low frequency - band levels decreasing by 8 dB per octave; high frequency - band levels increasing by 4 dB per octave.

*Statistically significant difference ($p<0.05$). Other differences in the table are not significantly different from 0.

Table 13 Mean Attenuation Difference (BCLB - REAT) by HPD Type and Frequency

	1/3 Octave Band Center Frequencies (Hz)								
HPD Type	125	250	500	1000	2000	3150	4000	6300	8000
Earplug									
Mean	0.3	-0.8	0.0	0.5	0.3	-4.0*	-3.2*	-2.2*	0.4
Std. Error	1.4	1.3	1.1	1.4	1.3	1.2	0.8	1.1	1.3
Earmuff									
Mean	2.9	2.6	-1.1	1.3	-2.3	2.5	2.8*	-0.6	-1.5
Std. Error	2.0	1.6	1.6	1.4	1.7	1.6	1.2	1.3	0.9
Canal cap									
Mean	4.0*	2.7	4.6*	3.3*	4.3*	3.5*	1.1	3.3*	1.4
Std. Error	1.7	1.7	1.5	1.9	1.9	1.5	1.2	1.3	1.1
Plug and muff									
Mean	0.1	-0.6	-4.5*	-1.6	0.3	-2.7	-4.2*	1.8	0.3
Std. Error	1.7	1.7	1.5	1.9	1.9	1.5	1.2	1.3	1.1

*Statistically significant difference ($p<0.05$). Other differences in the table are not significantly different from 0.

Table 14 Percentage of Attenuation Differences Less Than 5 dB by Subject and HPD Type

Subject	Earplugs	Canal caps	Earmuffs	Earplugs & Earmuffs	Mean
1	33%	NA	33%	67%	44%
2	78	NA	78	NA	78
3	NA	NA	67	44	56
4	44	NA	78	22	48
5	33	NA	67	33	44
6	22	NA	33	22	26
7	78	NA	33	89	67
8	78	NA	56	78	70
9	0	NA	33	11	15
10	67	NA	56	NA	61
11	78	NA	78	33	63
12	78	NA	56	78	70
13	33	67	NA	33	44
14	44	100	78	NA	74
15	67	44	78	89	69
16	78	67	NA	22	56
17	44	33	56	89	56
18	67	44	67	56	58
19	NA	11	22	NA	17
20	67	56	NA	67	63
21	44	33	33	NA	37
22	78	56	NA	78	70
23	78	44	33	11	50
24	44	33	NA	78	52
Mean	56	54	56	53	55
Mean*	59	54	57	56	57

*Mean values as computed without using data from subject 9.

Table 15 Percentage of Attenuation Differences Greater Than 10 dB by Subject and HPD Type

Subject	Earplugs	Canal caps	Earmuffs	Earplugs & Earmuffs	Mean
1	22%	NA	22%	0%	15%
2	0	NA	0	NA	0
3	NA	NA	0	11	6
4	0	NA	11	22	11
5	0	NA	0	0	0
6	0	NA	0	11	4
7	0	NA	0	0	0
8	0	NA	0	0	0
9	56	NA	33	78	56
10	0	NA	0	NA	0
11	11	NA	0	22	11
12	0	NA	0	0	0
13	11	0	NA	11	7
14	0	0	0	NA	0
15	0	11	0	11	6
16	11	11	NA	22	15
17	11	11	33	0	14
18	0	0	0	0	0
19	NA	22	22	NA	22
20	11	11	NA	0	7
21	0	22	22	NA	15
22	0	0	NA	0	0
23	0	0	11	22	8
24	22	0	NA	0	7
Mean	9	10	8	11	9
Mean*	5	10	7	7	7

*Mean values as computed without using data from subject 9.

Table 16 Correlation Coefficients for Subjects' Percentage of Attenuation Differences Less Than 5 dB by HPD Types

	Earplugs	Earmuffs	Canal Caps	Earplugs and Earmuffs
Earplugs	1.00			
Earmuffs	0.33 (0.19)	1.00		
Canal Caps	-0.04	0.69	1.00	
Earplugs and earmuffs	0.38 (0.23)	0.12 (-0.02)	-0.53	1.00

Note: Figures in parentheses are correlation coefficients computed without subject 9, who had an abnormally low percentage of attenuation differences less than 5 dB (see text).

Table 17 Correlation Coefficients for Subjects' Percentage of Attenuation Differences Greater Than 10 dB by HPD Types

	Earplugs	Earmuffs	Canal Caps	Earplugs and Earmuffs
Earplugs	1.00			
Earmuffs	0.69 (0.51)	1.00		
Canal Caps	-0.06	0.63	1.00	
Earplugs and earmuffs	0.71 (-0.08)	0.49 (-0.08)	0.09	1.00

Note: Figures in parentheses are correlation coefficients computed without subject 9, who had an abnormally low percentage of attenuation differences less than 5 dB (see text).

Table 18 Distribution of Differences in Threshold or Loudness Balance Levels on Successive Determinations

Type of test	0 dB	2 dB	>2 dB
REAT - open ears	35%	64%	1%
REAT - earplugs	34	62	4
REAT - canal caps	32	66	2
REAT - earmuffs	33	66	1
REAT - earplugs & earmuffs	37	62	1
REAT - all tests	34	65	1
BCLB - open ears	33	65	2
BCLB - earplugs	35	62	3
BCLB - canal caps	29	70	1
BCLB - earmuffs	36	61	3
BCLB - earplugs & earmuffs	36	62	2
BCLB - all tests	32	66	2

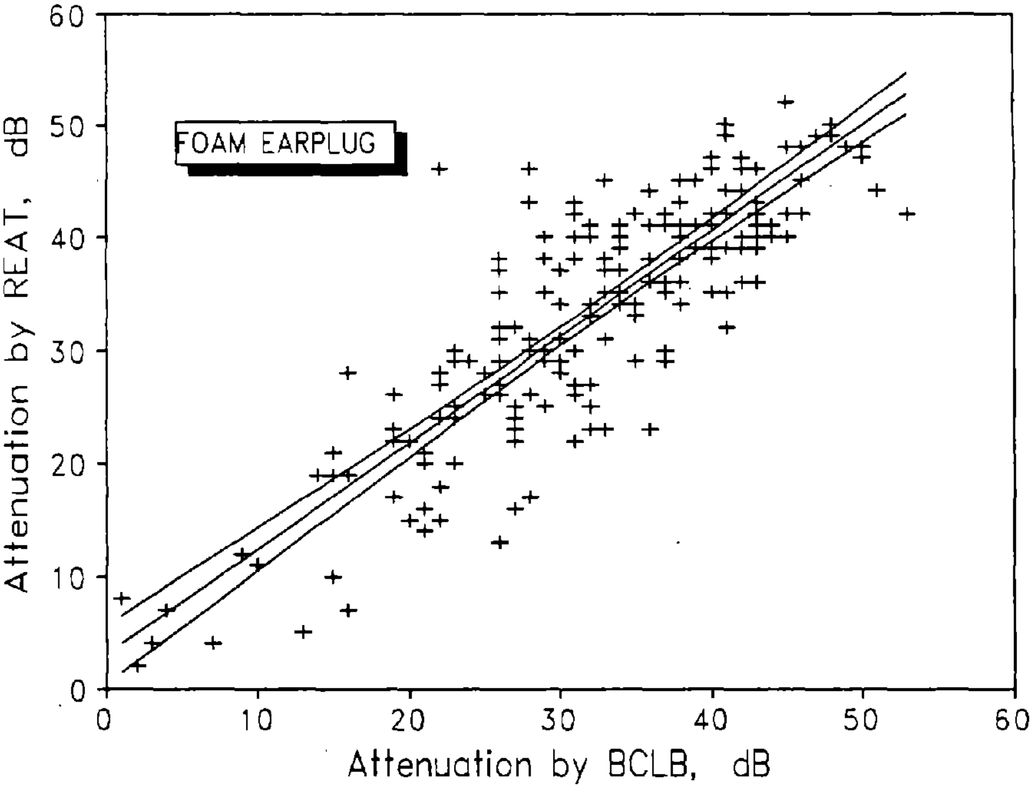

Figure 9. Attenuation as measured by BCLB and REAT with earplugs for 22 subjects, each at 9 frequencies from 125 to 8000 Hz. The diagonal lines are the linear least-squares regression line with its 95% confidence bands.

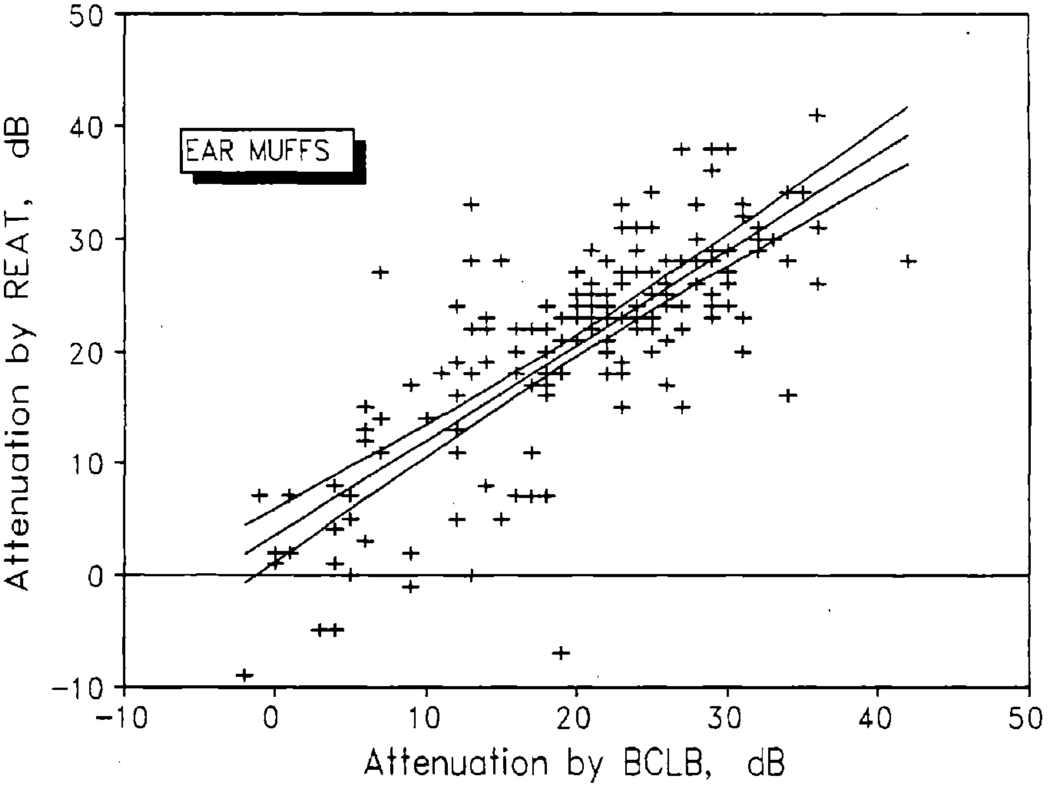

Figure 10. Attenuation as measured by BCLB and REAT with earmuffs for 19 subjects, each at 9 frequencies from 125 to 8000 Hz. The diagonal lines are the linear least-squares regression line with its 95% confidence bands.

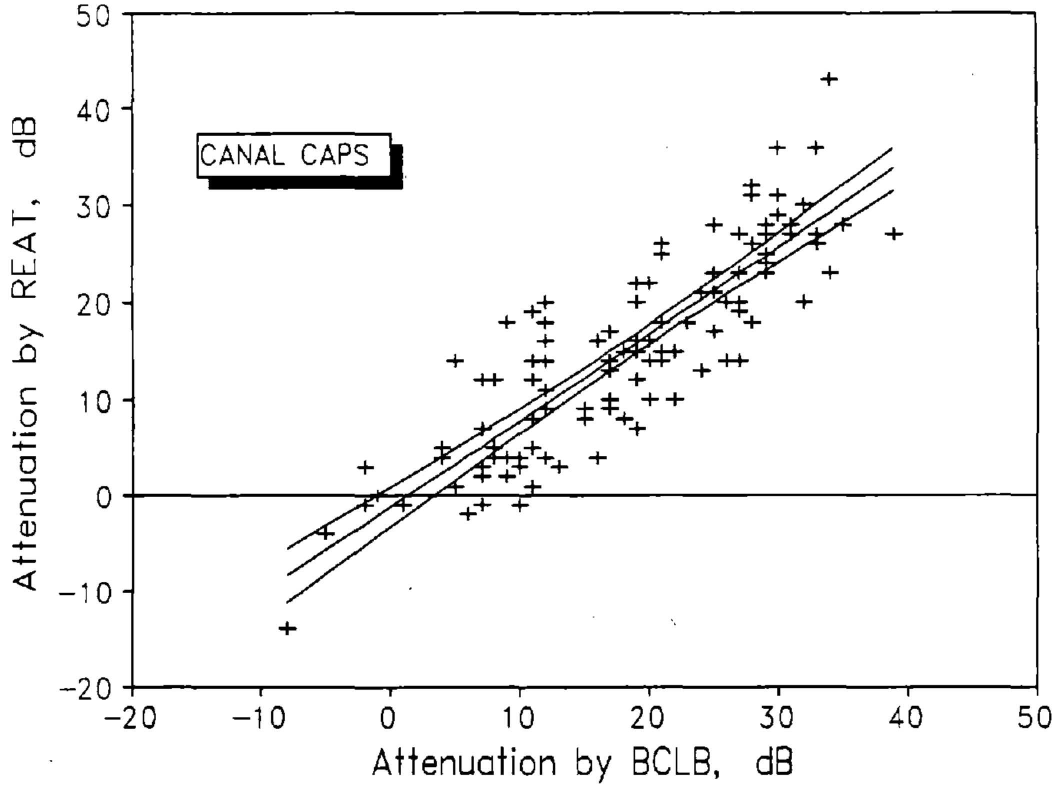

Figure 11. Attenuation as measured by BCLB and REAT with canal caps for 12 subjects, each at 9 frequencies from 125 to 8000 Hz. The diagonal lines are the linear least-squares regression line with its 95% confidence bands.

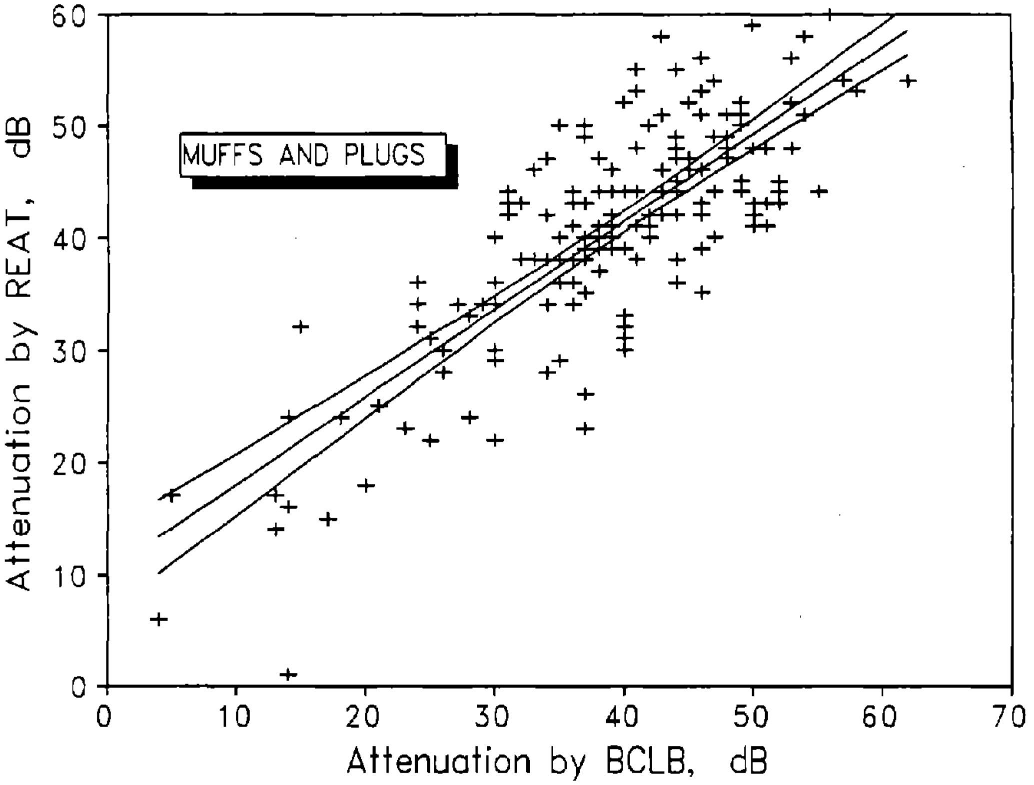

Figure 12. Attenuation as measured by BCLB and REAT with earmuffs and earplugs combined for 19 subjects, each at 9 frequencies from 125 to 8000 Hz. The diagonal lines are the linear least-squares regression line with its 95% confidence bands.

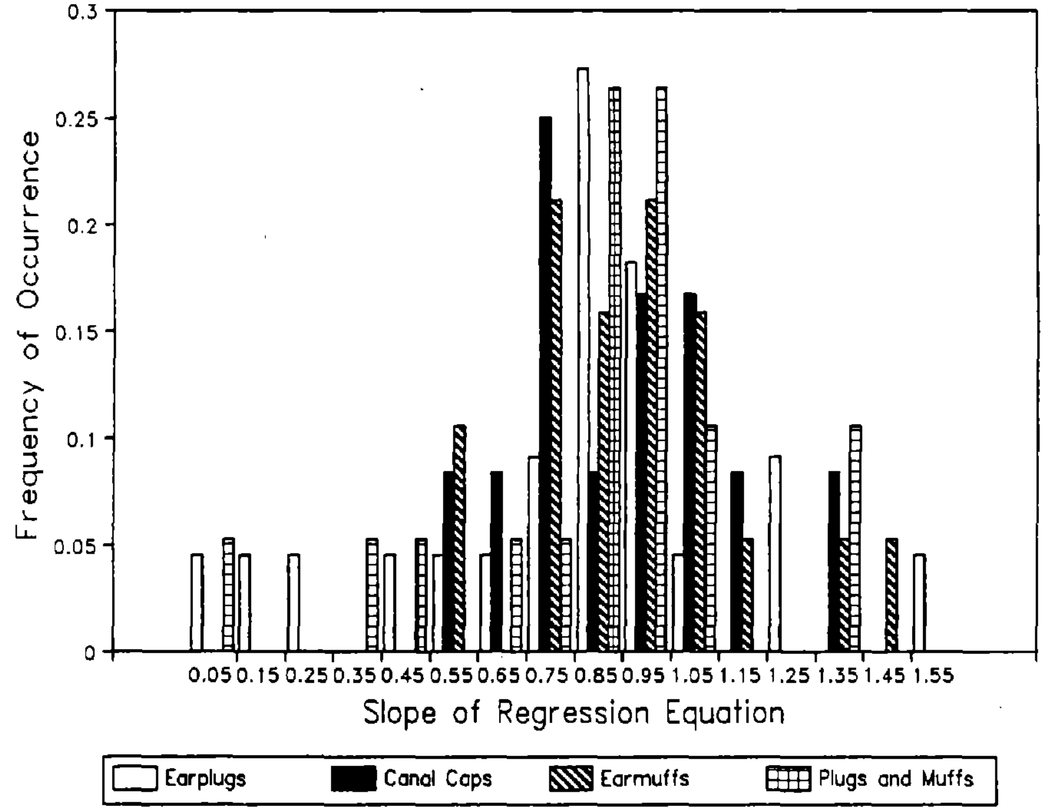

Figure 13. Histogram of the slopes of the regression equations (for each subject) for prediction of attenuation measured by REAT from attenuation measured by BCLB. The slopes were rounded to the nearest 0.05 for creation of the histogram.

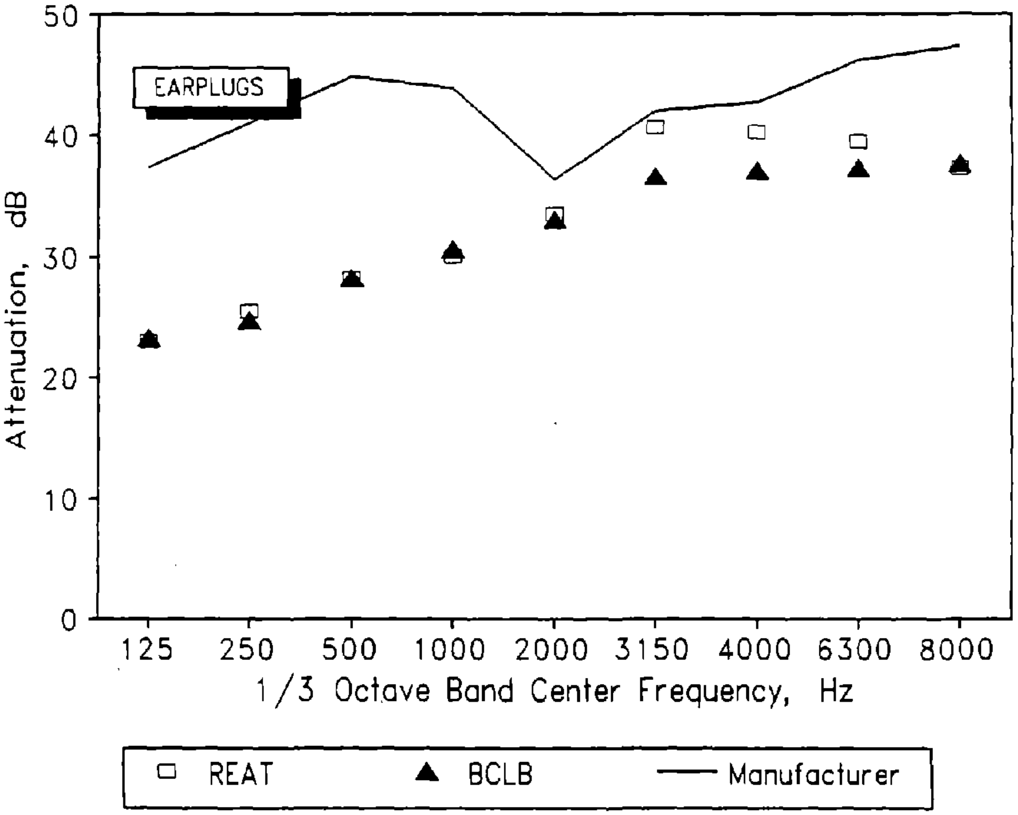

Figure 14. The mean attenuation at each frequency as measured by BCLB and REAT with earplugs for 22 subjects. The solid line is the mean attenuation as stated by the earplug manufacturer, based on REAT testing of a panel of subjects under optimum fitting conditions.

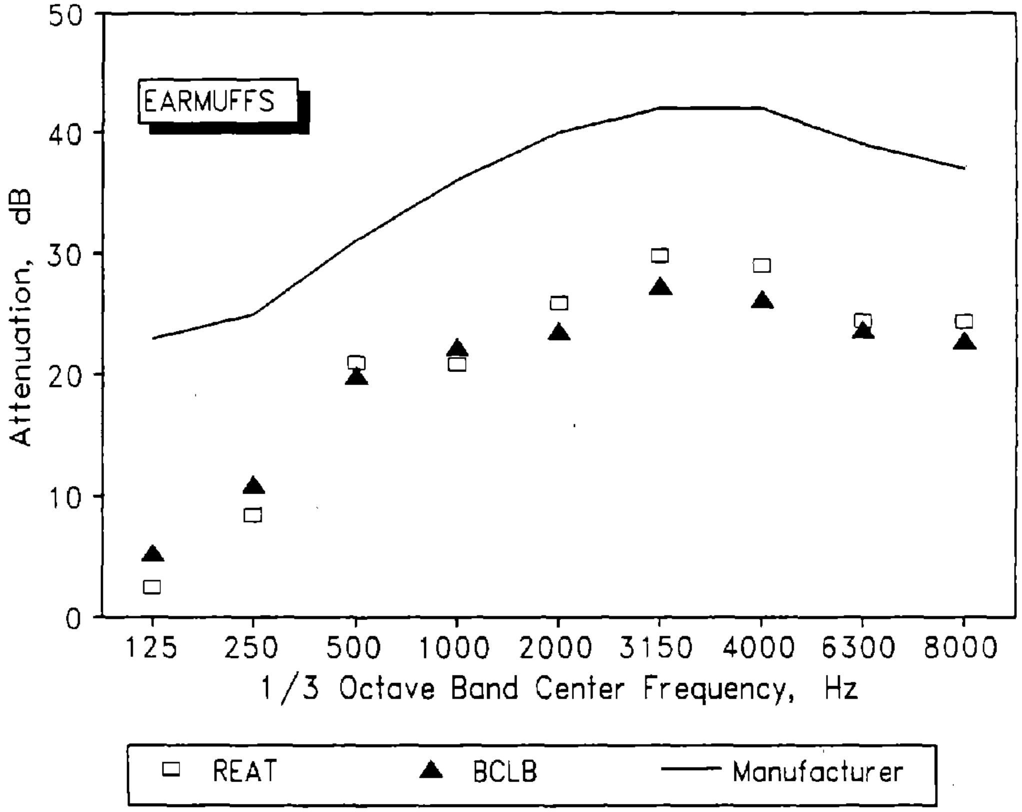

Figure 15. The mean attenuation at each frequency as measured by BCLB and REAT with earmuffs for 19 subjects. The solid line is the mean attenuation as stated by the earmuff manufacturer, based on REAT testing of a panel of subjects under optimum fitting conditions.

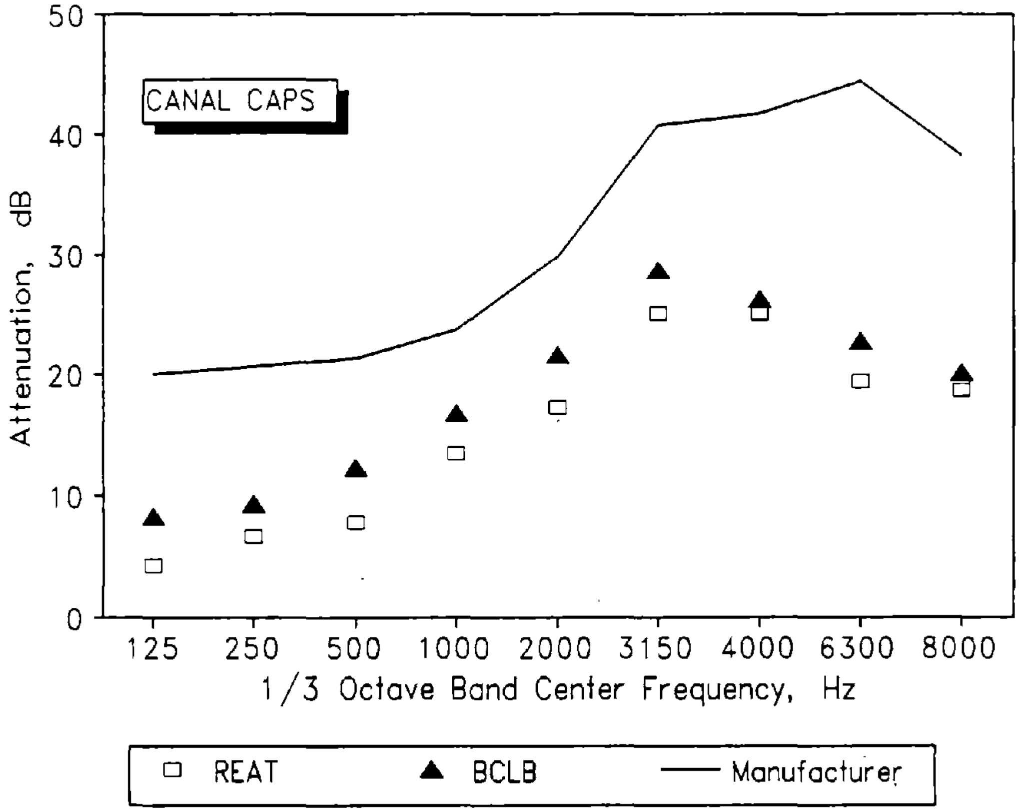

Figure 16. The mean attenuation at each frequency as measured by BCLB and REAT with canal caps for 12 subjects. The solid line is the mean attenuation as stated by the canal caps manufacturer, based on REAT testing of a panel of subjects under optimum fitting conditions.

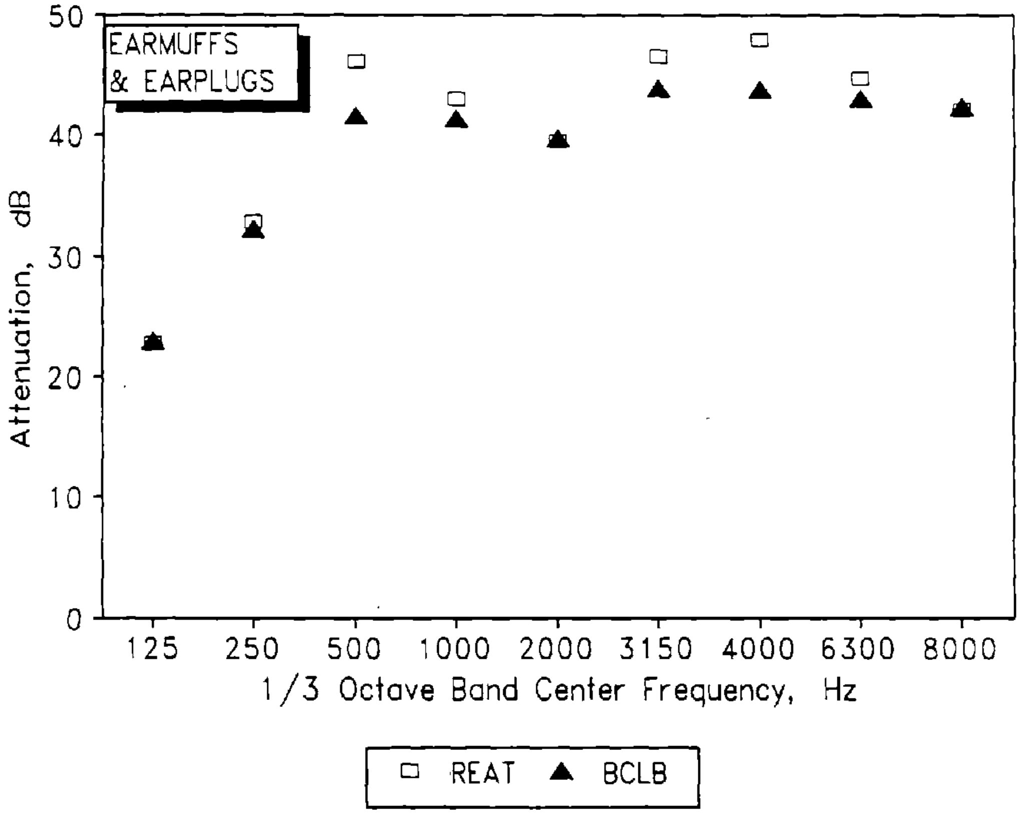

Figure 17. The mean attenuation at each frequency as measured by BCLB and REAT with the combination of earplugs and earmuffs for 19 subjects.

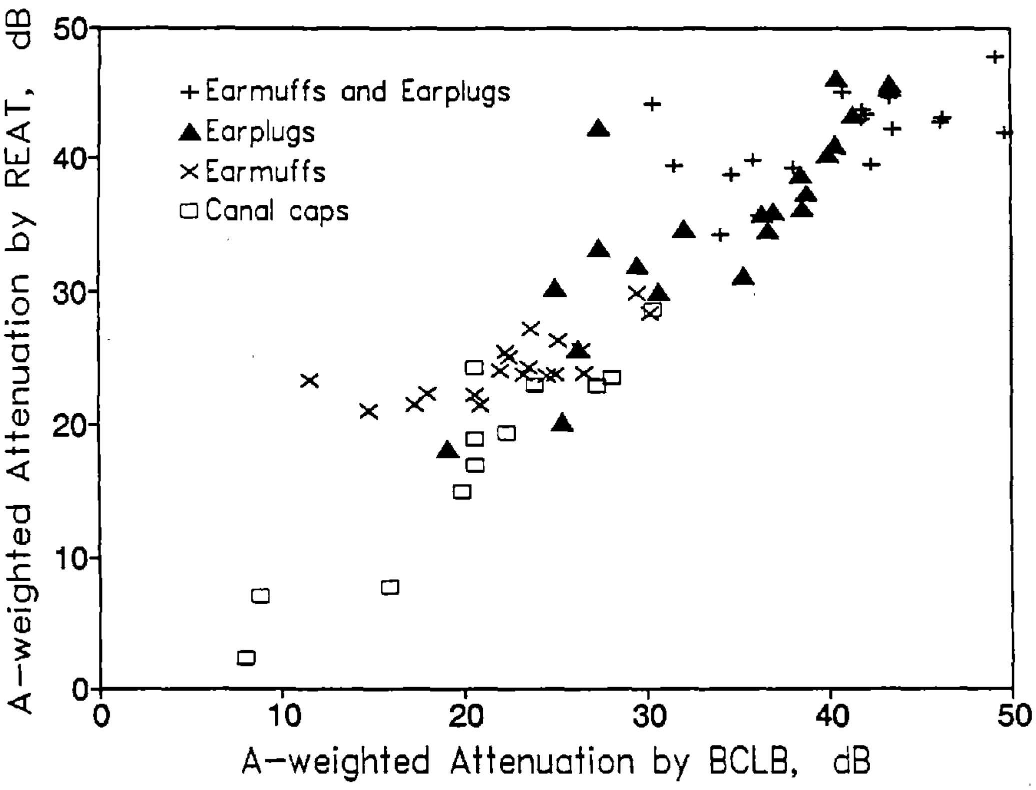

Figure 18. A-weighted attenuation as measured by BCLB and REAT when applied to a flat noise spectrum (equal octave band sound pressure levels).

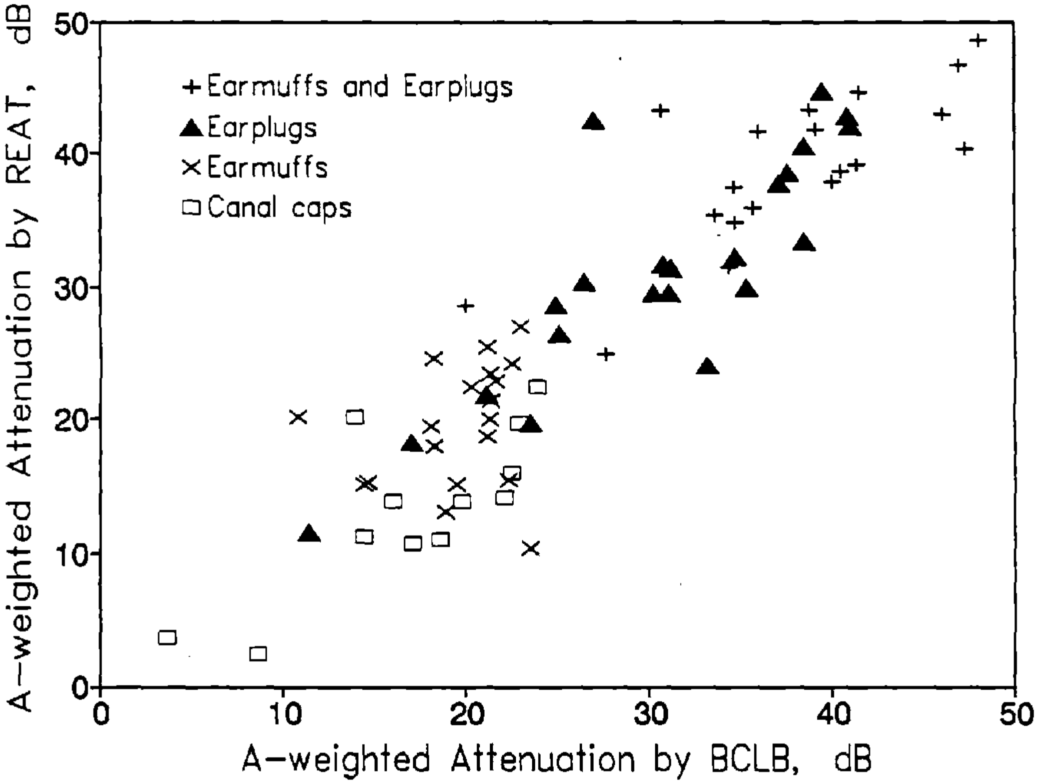

Figure 19. A-weighted attenuation as measured by BCLB and REAT when applied to a high frequency noise spectrum (octave band sound pressure levels increasing by 4 dB/octave from 125 Hz to 8000 Hz).

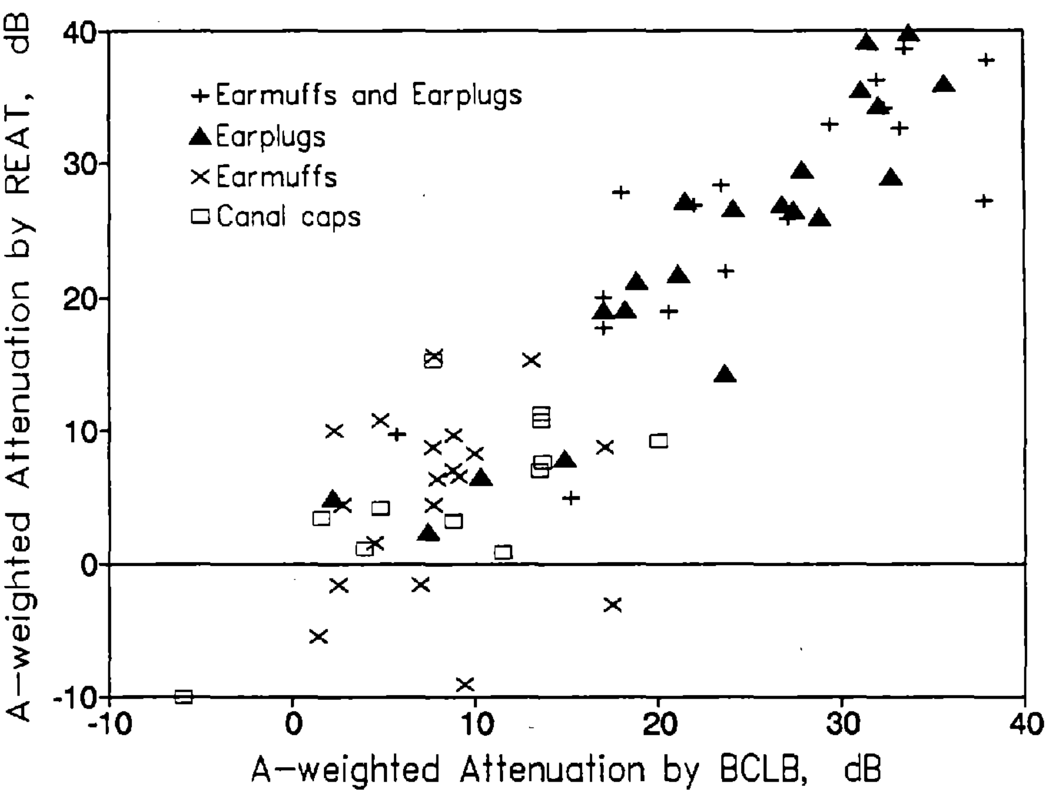

Figure 20. A-weighted attenuation as measured by BCLB and REAT when applied to a low frequency noise spectrum (octave band sound pressure levels decreasing by 8 dB/octave from 125 Hz to 8000 Hz).

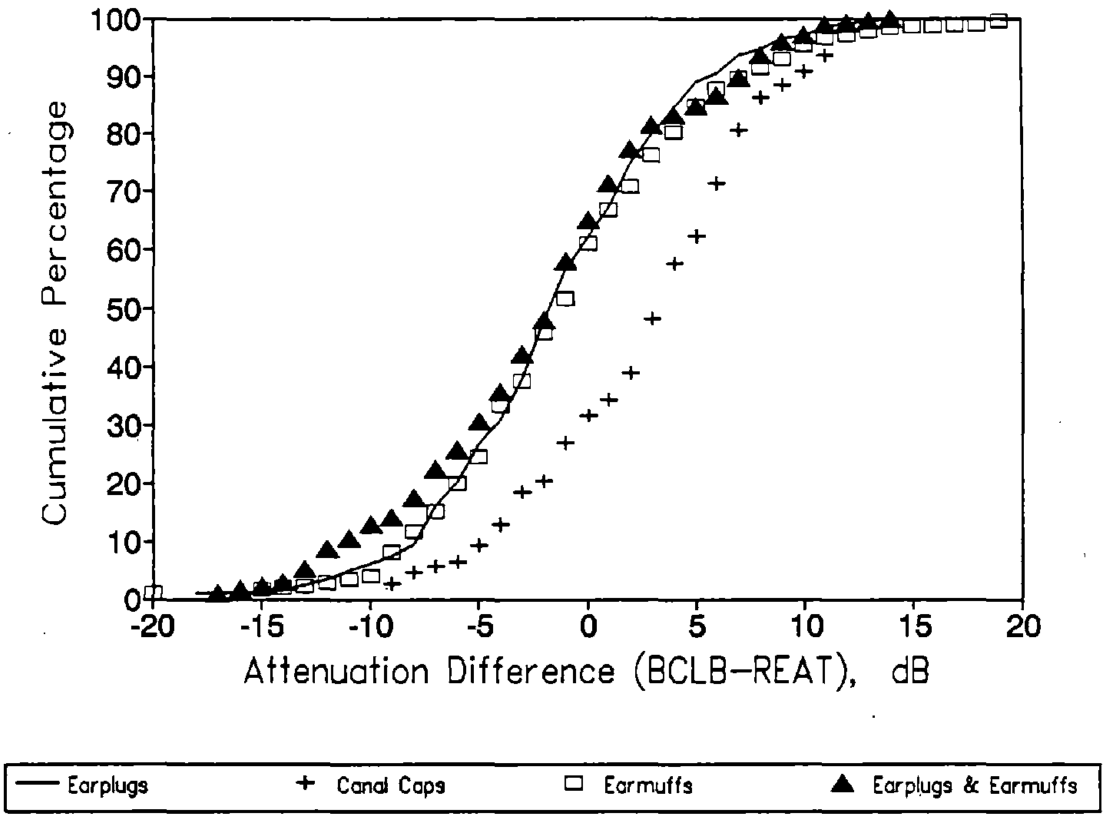

Figure 21. Cumulative distributions of the attenuation differences (BCLB – REAT) for the four different HPD types.

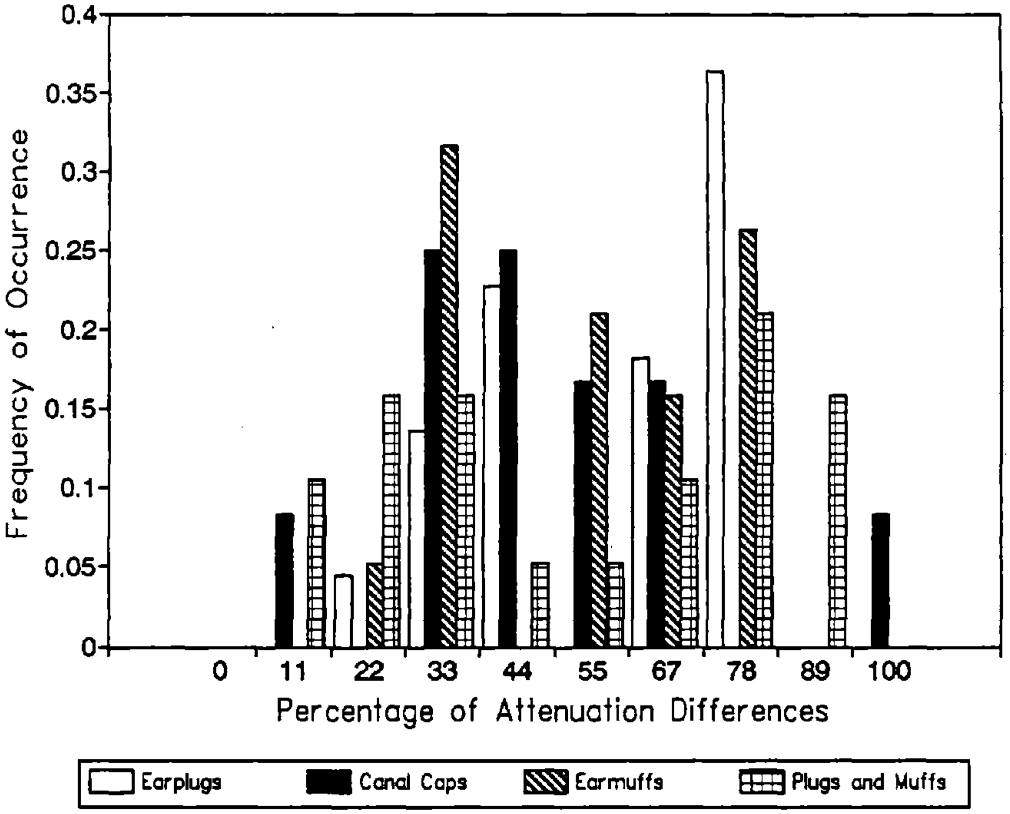

Figure 22. Histogram of the percentage of attenuation differences (BCLB - REAT) less than 5 dB for each subject. For example, approximately 37% of subjects wearing earplugs had 78% of pairs of attenuation values within 5 dB.

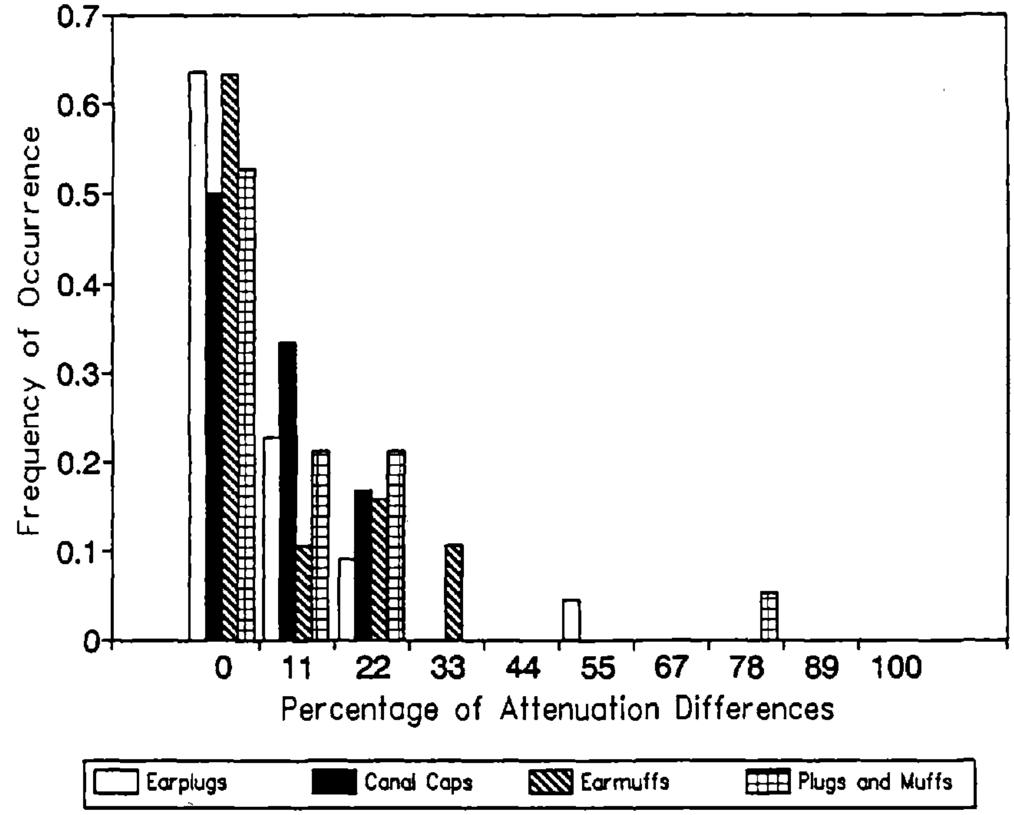

Figure 23. Histogram of the percentage of attenuation differences(BCLB – REAT) greater than 10 dB for each subject. For example, approximately 64% of subjects wearing earplugs had no pairs of attenuation values differing by more than 10 dB.

REFERENCES

1. Berger, E.H.: Earlog #20 -- The Naked Truth About NRRs. Southbridge, MA: Cabot Safety Corp., 1993.

2. Casali, J.G. and M. Park: Laboratory versus Field Attenuation of Selected Hearing Protectors. Sound and Vibration, 25(10):28-38 (1991).

3. Lempert, B.L. and R.G. Edwards: Field Investigations of Noise Reduction Afforded by Insert-Type Hearing Protectors. Am. Ind. Hyg. Assoc. J. 44:894-902 (1983).

4. Park, M. and J.G. Casali: A Controlled Investigation of In-field Attenuation Performance of Selected Insert, Earmuff, and Canal Cap Hearing Protectors. Human Factors 33(6):693-714 (1991).

5. Rink, T.L.: Hearing Protection and Speech Discrimination in Hearing-Impaired Persons. Sound and Vibration 13(1):22-24 (1979).

6. Berger, E.H.: Methods of Measuring the Attenuation of Hearing Protection Devices. J. Acoust. Soc. Am. 79:1655-1687 (1986).

7. Wheeler, P.D. and D. Smeatham: On Spatial Variability in the Attenuation Performance of Active Hearing Protectors, Applied Acoustics 36:159-65 (1992).

8. Casali, J.G. and M.-Y. Park: Effects of Work Conditions Simulated in a Laboratory Environment and Wearer Fit on Attenuation of Slow-Recovery Foam Earplugs. J. of Sound and Vibration 143(1):153-165 (1990)

9. Kryter, K.D.: Physiological, Psychological, and Social Effects of Noise. Washington, DC: National Aeronautics and Space Administration, 1984, pp. 188-191.

10. Fleming, R.M.: A New Procedure for Field Testing of Earplugs for Occupational Noise Exposure. Sc.D. Thesis at Harvard School of Public Health, Boston, MA. (1980).

11. Chillery, J.A.: Measurement of the Real-Ear Attenuation of Hearing Protectors According to the South African Standard SABS 572 1973. J. Sound Vib. 67(1):21-33 (1978).

12. Webster, J.C.: Ear Defenders: Measurement Methods And Comparative Results. Noise Control 1(5):34-42 (1955).

13. Weinreb, L. and M.L. Touger: Variation in Ear Protector Attenuation as Measured by Different Methods. J. Acoust. Soc. Am. 32:245-249 (1960).

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

15. Dirks, D.D. and J.G. Swindeman: The Variability of Occluded and Unoccluded Bone-Conduction Thresholds. J. Speech Hearing Res. 10:232-249 (1967).

16. Casali, J.G. and M. Park: A Regression-Based Methodology for Efficient Prediction of Broadband Attenuation of Hearing Protectors. Noise Control Eng. J. 38(3):97-108 (1992).

17. Newby, H.A. and G.R. Popelka: Audiology. Englewood Cliffs, NJ: Prentice Hall, 1992. pp. 243-249.

18. "Occupational noise exposure: Hearing Conservation Amendment," Federal Register 48:46 (8 March 1983) pp. 9738-9785.

19. Houtsma, M.A.; Rossing, T.D.; Wagenaars, W.M.: Auditory Demonstrations. Eindhoven, The Netherlands: Institute for Perception Research, 1987.

20. American National Standards Institute: ANSI S12.6-1984: Method for the Measurement of the Real-Ear Attenuation of Hearing Protectors. New York: American National Standards Institute, 1984.

21. Frank, T.; Williams, D.L.: Ambient Noise Levels in Industrial Audiometric Test Rooms. Am. Ind. Hyg. Assoc. J. 55(5):433-437 (1994).

22. Beranek, L.L., ed: Noise and Vibration Control, revised edition, Washington, DC: Institute of Noise Control Engineering, 1988. pp. 575-586.

23. Carter, N.L.; Upfold, G.: Comparison of Earphone and Sound Field Methods for Estimating Noise Attenuation of Foam Earplugs. Am. Ind. Hyg. Assoc. J. 54:307-312 (1993).

24. Waugh, R.: dBA Attenuation of Hearing Protectors. J. Acoust. Soc. Am. 53(2):440-447 (1973).

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PUBLICATIONS

The research work described in this report has also been described in the dissertation of the co-investigator (Rimmer, T.W.: A New Method for Measurement of Hearing Protector Attenuation: Bone Conduction Loudness Balance. Sc.D. Thesis at the University of Massachusetts Lowell, Lowell, MA 1995). Manuscripts will also be submitted for publication in industrial hygiene journals.