Validation of an acoustic head simulator for the evaluation of personal hearing protection devices

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This study, approved by the DRDC Human Research Ethics Committee, was conducted in conformity with the Tri-Council Policy Statement: Ethical Conduct of Research Involving Human Subjects.

Abstract

A study was carried out to assess the validity of using an acoustic test fixture (ATF) designed to measure the sound reduction afforded by personal hearing protection devices. The ATF under review consists of a head simulator cast from aluminum-filled epoxy and covered with artificial skin. Cavities milled out on either side allow for the insertion of ear modules that incorporate a mechanical reproduction of human aural tissues. The ear canal is terminated by Zwislocki coupler and Etymotic ER-11 measurement microphone and models the impedance of the human ear. The experiment was carried out in a semi-reverberant chamber. On two separate occasions scheduled four months apart, the right ear of the ATF was fitted with an earmuff (E-A-R 3000), an earplug (E-A-R Classic foam plug), and the muff and plug in combination. The non test ear was fitted with an E-A-R Classic plug. The stimulus was continuous pink noise, presented free-field at a level of 86 dB SPL using a bank of low, middle and high frequency speakers. Monaural sound level measurements were made under each of these conditions, as well as with the test ear unoccluded. These were replicated three times within each of the two test sessions using two different settings of the measurement microphone, diffuse-field equalization and flat frequency response. Measurements were recorded and subsequently subjected to a one-third octave band analysis from 12.5 Hz to 20 kHz. The results showed that the measurements were highly stable within and across sessions. Differences in the sound pressure level due to the setting of the measurement microphone were in line with published specifications. These did not affect insertion loss values. When corrected for the effects of bone conduction, occlusion and physiological masking, insertion loss values (the difference between unoccluded and protected levels), closely matched real-ear attenuation at threshold data collected from human observers in the range of 500 Hz to 8 kHz.

Résumé

Une étude a été effectuée afin d'évaluer la validité de l'utilisation d'un « dispositif d'essai acoustique » (*acoustic test fixture*, ou ATF) destiné à mesurer l'affaiblissement acoustique offert par des dispositifs de protection personnelle de l'ouie. L'ATF à l'étude consiste en un simulateur de tête époxy chargé d'aluminium et recouvert de peau artificielle. Les cavités de chaque côté permettent l'insertion de modules d'oreilles qui reproduisent les mécanismes des tissus auriculaires humains. Le conduit auditif externe, qui aboutissait dans un coupleur de Zwislocki et un micro de mesure Etymotic ER-11, a servi de modèle d'impédance acoustique de l'oreille humaine. L'expérience a eu lieu dans une chambre semi-réverbérante. Au cours de deux expériences distinctes, effectuées à quatre mois d'intervalle, on a successivement placé sur l'oreille droite de l'ATF un cache-oreilles antibruit (E.A.R. 3000), un bouchon d'oreille (bouchon-mousse E.A.R. Classic) et à la fois le cache-oreilles et le bouchon d'oreille. On a posé un bouchon-mousse E.A.R. Classic sur l'oreille non testée. Le stimulus était un bruit rose continu, présenté dans une chambre sourde à 86 dB SPL au moyen d'un ensemble de hauts-parleurs à fréquences basses, moyennes et hautes. Les mesures du niveau sonore monaural ont été effectuées avec chacun des dispositifs, les deux ensemble ainsi qu'avec aucun des deux. On a répété les essais trois fois durant chacune des deux séries d'essais en utilisant deux réglages différents pour le micro de mesure, l'égalisation acoustique en champ diffus et la réponse en fréquence uniforme. Les mesures ont été enregistrées puis soumises à une analyse par bande de tiers d'octave de 12,5 Hz à 20 kHz. Les résultats ont démontré que les mesures étaient très stables durant chacune des séries d'essais ainsi que d'une série à l'autre. Les différences au chapitre de la pression acoustique dues aux réglages du micro de mesure étaient conformes aux spécifications publiées. Ces différences n'ont pas influé sur la perte d'insertion. Après correction pour tenir compte des effets de la conduction osseuse et de l'occlusion et du masquage physiologique, la perte d'insertion (différence selon que le sujet portait ou non les dispositifs de protection de l'ouïe) présentait une corrélation étroite avec l'atténuation acoustique effective au niveau liminaire observé chez des sujets humains dans le plage de 500 Hz à 8 kHz.

Executive summary

This study determined the validity of using an acoustic test fixture (ATF) in place of human subjects to assess the sound reduction afforded by personal hearing protection devices. The ATF allows for the measurement of sound reduction (insertion loss) at supra threshold levels for both continuous and impulse noise that might be outside the frequency range of or injurious to human hearing. Potential drawbacks are that the ATF may not accurately model human peripheral auditory pathways and does not provide an opportunity to assess the variability in outcome due to individual differences in the fit of candidate devices. The ATF that was used in the present investigation was developed at the Institute of Biomedical Engineering, University of Toronto, under contract to DRDC Toronto. It comprises a head simulator cast from aluminum-filled epoxy and covered with artificial skin. The head is supported by a compliant neck module, attached to a standard KEMAR torso mounted on an adjustable stand. It is separable into two halves along the mid sagittal plane with a hollow interior for instrumentation. Cavities milled out on either side accommodate snap in ear modules. The test ear canal is terminated by a Zwislocki coupler. The experiment was conducted in a semi-reverberant sound isolation room. The stimulus was 86 dB SPL continuous pink noise presented over a bank of speakers facing the ATF at a distance of about 4 m. Monaural sound level measurements were made at the "eardrum" using an Etymotic ER-11 microphone set in one of two modes: flat frequency and equalized flat frequency response. The latter measures the simulated diffuse-field response. Measurements were made with the pinna of the test ear unoccluded and protected with an E-A-R 3000 earmuff, E-A-R Classic foam earplug and the muff and plug in combination. The non test ear was fitted with an E-A-R Classic foam plug. The response was recorded for later third octave analysis at thirty-three centre frequencies from 12.5 Hz to 20 kHz. Insertion loss values were calculated as the difference between the protected and unoccluded measurement at each frequency. Each of the eight ear by microphone setting conditions was replicated three times in close succession so that the reliability of the outcome could be assessed. The devices were refit for each measurement. The entire experiment was repeated after an interval of four months. The results indicated that the sound level measurements were highly repeatable. Within each session, standard deviations were less than 2 dB for the most part. Across test sessions, the differences between mean values were generally no greater than 6 dB. As specified by the manufacturer, sound levels were less for the diffuse-field equalization setting than the flat frequency response setting of the microphone, ranging from 2 to 15 dB across frequency bands, with a maximum at 2.5 kHz. The microphone setting did not affect the insertion loss values. For the muff, insertion loss values were generally within 4 dB of published sound attenuation results derived from human subjects experiments from 125 Hz to 8 kHz. Differences as large as 18 dB were observed for the plug. Closer fits in the order of 5 dB were obtained from 500 Hz to 8 kHz when insertion loss values were corrected for the limiting effects of human bone conduction, perceptual masking effects and physiological noise at low frequencies.

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Sommaire

Cette étude a porté sur la validité de l'utilisation d'un « dispositif d'essai acoustique » (*acoustic test fixture*, ou ATF) au lieu de sujets humains pour mesurer l'affaiblissement acoustique offert par des dispositifs de protection personnelle de l'ouïe. L'ATF permet de mesurer l'affaiblissement acoustique (perte d'insertion) à des niveaux supraliminaires, tant pour les bruits continus que pour les bruits impulsifs qui pourraient se situer à l'extérieur du spectre sonore de l'humain ou causer des lésions chez l'humain. Parmi les inconvénients potentiels, il se peut que l'ATF ne reproduise pas efficacement le système auditif périphérique de l'humain et qu'il ne permette pas d'évaluer la variation des résultats due aux différences individuelles en ce qui a trait à l'ajustement des dispositifs candidats. L'ATF utilisé dans le cadre de la présente étude a été mis au point à l'Institut de génie biomédical de l'Université de Toronto en sous-traitance pour RDDC Toronto. Il consiste en un simulateur de tête époxy chargé d'aluminium et recouvert de peau artificielle. La tête est soutenue par un module de cou souple rattaché à un torse de mannequin KEMAR monté sur un support ajustable. La tête se divise en deux dans l'axe du plan sagittal médian; elle est creuse afin qu'on puisse y placer des instruments. Les cavités de chaque côté permettent l'insertion de modules d'oreilles. Le conduit auditif externe servant à l'essai aboutissait dans un coupleur de Zwislocki. L'expérience a eu lieu dans une chambre semi-réverbérante insonorisée. Le stimulus était un bruit rose continu, présenté dans une chambre sourde à 86 dB SPL au moyen d'un ensemble de hauts-parleurs disposés devant l'ATF, à une distance d'environ 4 m. Les mesures du niveau sonore monaural ont été prises au niveau de la « membrane du tympan » à l'aide d'un micro Etymotic ER-11 réglé dans un des deux modes suivants : fréquence uniforme et réponse en fréquence uniforme égalisée. Le mode réponse en fréquence uniforme égalisée mesure la réponse en champ diffus simulé. Les mesures ont été prises dans les conditions suivantes : pavillon de l'oreille testée non bouché, pavillon protégé par le cache-oreilles antibruit E.A.R. 3000, pavillon protégé par le bouchon-mousse E.A.R. Classic et pavillon protégé à la fois par le cache-oreilles et le bouchon-mousse. On a posé un bouchon-mousse E.A.R. Classic sur l'oreille non testée. La réponse a été enregistrée en vue d'une analyse ultérieure par bande de tiers d'octave faisant appel à 33 fréquences centrales allant de 12,5 Hz à 20 kHz. La perte d'insertion a été calculée comme la différence avec et sans les dispositifs de protection de l'ouïe à chaque fréquence. Chacune des huit conditions d'essai a été reproduite trois fois à des intervalles rapprochés, de manière que la fiabilité des résultats puisse être évaluée. Les dispositifs ont été ajustés de nouveau pour chaque mesure. L'expérience entière a été répétée après un intervalle de quatre mois. Les résultats ont montré que les mesures du niveau sonore étaient hautement reproductibles. Les écarts types ont été inférieurs à 2 dB durant la plupart des séances d'essai. Les différences entre les valeurs moyennes d'une séance d'essai à l'autre n'ont généralement pas dépassé 6 dB. Tel qu'indiqué par le fabricant, les niveaux sonores ont été moins élevés lorsque le micro était en mode égalisation acoustique en champ diffus que lorsqu'il était en mode réponse en fréquence uniforme, variant de 2 à 15 dB selon la fréquence utilisée (la plus haute étant 2,5 kHz). Le réglage du micro n'a pas influé sur la perte d'insertion. Avec le cache-oreilles antibruit, la perte d'insertion s'est généralement située à 4 dB ou moins des résultats publiés des essais d'atténuation acoustique sur des sujets humains à des fréquences de 125 Hz à 8 kHz. On a relevé des différences allant jusqu'à 18 dB avec le bouchon-mousse. On a obtenu des concordances de l'ordre de 5 dB pour la gamme de 500 Hz à 8 kHz après avoir corrigé les valeurs de perte d'insertion en fonction des effets limitatifs de

la conduction osseuse chez l'humain, des effets du masquage perceptuel et du bruit physiologique à des fréquences basses.

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Introduction

The main method of assessing the efficacy of hearing protective earplugs and earmuffs is the measurement of real-ear attenuation at threshold in human observers or REAT (Berger, 2000). Using this method sound attenuation is calculated by taking the difference in hearing threshold with and without the protectors fitted, at a wide range of frequencies (CSA, 2002). The greater the difference (relative elevation in hearing threshold), the greater the sound attenuation achieved with the device. It has been shown that REAT measurements may be affected by the fit of the device (Riko and Alberti, 1982). In the case of earplugs, the attenuation achieved may be less than the manufacturers' specifications if the plug has not been properly inserted into the ear canal, if the size of the plug is too small or too large for the individual user, if the plug becomes unseated during prolonged use or if the device is not maintained properly. In the case of muffs, the attenuation achieved may be compromised by poor sealing of the muffs with the sides of the head in the region of the ears. A poor seal may result from insufficient headband tension, deterioration of the ear cushions or the use of other safety gear in combination such as eyeglasses or respirators (Abel et al., 2002). Generally, the attenuation achieved will be greater when hearing protection devices are fitted by trained professionals or with instructions from trained professionals than by the user. Various formulae have been promulgated to de-rate manufacturers' specifications to provide a closer approximation to real-world values (Berger, 2000).

The potential for measurement error due to subject variables may be avoided by using an acoustic test fixture (ATF) that models the human head and ear. Potential drawbacks are (1) the ATF may provide a poor model of one or more of the human peripheral auditory pathways (Berger, 2000), and (2) the ATF does not provide a way to assess the effect of variability in the size of the human head and ears on the sound attenuation afforded by the hearing protector (Abel et al., 1990; Abel et al, 2002). Important advantages of using an ATF are that (1) it allows for the measurement of sound reduction at supra threshold levels that are realistic of the real world, (2) it can be used in situations where the type and level of the noise (e.g., impulse noise) may be injurious to human hearing (Crabtree, 1992), and (3) sound reduction can be assessed at frequencies that are generally considered to be outside the range of adult human hearing. Typically, REAT measurements are made between 250 Hz and 8 kHz.

The binaural ATF that was used for the present investigation was developed under contract for DRDC Toronto by the Institute of Biomedical Engineering, University of Toronto. Detailed descriptions of the design, construction and validation of the original monaural version and the later binaural version currently in use have been published previously (Giguère, 1986; Kunov et al., 1988; Giguère and Kunov 1989; Kunov and Giguère, 1989; Crabtree, 1992). The binaural ATF comprises a modified Knowles Electronics Manikin for Acoustic Research (KEMAR). The head, proportioned to model the average Caucasian male head, is cast from aluminum-filled epoxy, covered with artificial skin and incorporates a mechanical reproduction of human aural tissues (Kunov et al., 1988; Kunov and Giguère, 1989). It is supported by a compliant neck which is attached to a standard KEMAR torso mounted on an adjustable stand. The compliant neck models the natural decoupling between the human neck and torso. Isolation from external vibration is a by-product of this model. The head simulator is separable into two symmetrical halves along the mid sagittal plane. The inside is hollow in order to accommodate microphones and preamplifier cables (see Figures 1 and 2). Cavities milled out on either side allow for the insertion of the ear modules. The ear canal is terminated by a Zwislocki (model DB 100) coupler (Burkhard and Sachs, 1975), which is threaded to accommodate an Etymotic ½ inch microphone (ER-11) or Brüel and Kjaer measurement microphone (model 4134). The assembly models the acoustical impedance of the human ear. Previous validation studies have examined the effects of various parameters of the ATF including the use of artificial circumaural and intraaural skin and change in head configuration (Giguère and Kunov, 1989). These resulted in recommendations for improvements in the design which are incorporated in the version under current review.

The intent of the present investigation was to carry out further validation studies of the DRDC Toronto ATF. An experiment was designed to assess the effect on insertion loss (IL) from a conventional hearing protective earplug and earmuff of (1) two possible settings of the Etymotic microphone used to measure sound level, namely flat frequency response and diffuse-field equalization, and (2) repeated measurements conducted within the same session and four months apart. Insertion loss (IL) values were obtained at a wide range of frequencies for a standard earmuff and earplug. IL and REAT measurements may be compared. With REAT measurements in human subjects, the difference in sound level needed for threshold perception with and without a protector in place is assessed. The better the protector, the greater the shift towards higher thresholds. When using an ATF, sound level measurements are made at the termination of the artificial ear canal. The better the protector, the lower the level reaching the measurement microphone.

Methods and materials

Experimental design

The experiment was conducted in the Noise Simulation Laboratory located at DRDC Toronto. This facility is a semi-reverberant chamber, 10.55 metres (L) by 6.10 metres (W) by 3.05 metres (H). An array of speakers comprising eight Equity Sound Investment subwoofers (Model G218s), four Electrovoice Servodrive low range speakers (model Bass Tech 7) and four Electrovoice Delta Max speakers (model DMC 1152A) occupies the width of the shorter rear wall (see Figure 1). The choice of speakers allows the acoustic simulation of a wide range of Canadian Forces operational noise environments, in terms of both level and energy spectrum and in its current configuration has the capability of producing noise levels in excess of 130 dB SPL.

The ATF faced the speaker array at a distance of 4.35 metres. In selecting the position in the room, consideration was given to minimizing high-frequency fluctuations and major standing waves. The stand supporting the KEMAR torso was adjusted such that the height of the ears from the floor was 1.4 m**.** Cable holes in the bottom of the torso of the manikin were blocked with rubber stoppers and a 30-cm square of foam was placed inside the torso to minimize the contributions of possible indirect sound paths to the measurements.

Two hearing protectors were selected for testing, the E-A-R Classic foam earplug and E-A-R 3000 earmuff. These devices were readily available and relevant to the Canadian Forces. Pilot testing confirmed that good fits could be obtained with the ear simulator. It was recognized that the difference in temperature between the human and ATF ear canals could result in a difference in the expansion and seating of the plug. To minimize this difference, the plug was warmed under a light bulb prior to each insertion in the ear simulator.

The right ear of the ATF was tested under the following conditions: (1) unoccluded, (2) fitted with the plug, (3) fitted with the muff, and (4) fitted with the muff and plug in combination. Measurements were made at the right ear. The left ear simulator was fitted with an E-A-R plug throughout the experiment to minimize its possible contribution to the measurement. Pinnas for both ears were in place for all conditions. The muffs covered both the right and left ears. There were three replications of each condition within a single session lasting about three hours. The experiment was repeated after four months to test the stability of the measurements.

The stimulus was continuous pink noise (equal energy per octave) presented at a level of 86 dB SPL at the entrance to the ear. The noise was generated by a Brüel & Kjaer noise generator (model 1049). A series of sound level measurements were made at the 'ear drum' of the ATF at thirty-three third octave centre frequencies ranging from 12.5 Hz to 20 kHz under each of the four ear conditions with an Etymotic ½-inch microphone (model ER-11). Two settings of the microphone were investigated, flat frequency response and equalized flat frequency response (see Annex A). The latter mode is designed by the manufacturer for use with the DB100 Zwislocki coupler in KEMAR in situations where one wishes to reproduce the diffuse-field response of the ATF through earphones. That is, recordings made with diffuse-field equalization heard on high fidelity earphones would be spectrally correct. Switching between microphone modes was accomplished through an electronic filter box located between the microphone and a Brüel and Kjaer spectrum analyzer (Model 2133). Comparison of sound level measurements made with the microphone operating in the two modes allowed a confirmation of the manufacturer's specification.

Procedure

The four ear conditions were tested in the following order in both test sessions: 1) E-A-R 3000 muff, 2) E-A-R Classic foam earplug, 3) E-A-R 3000 muff and E-A-R Classic earplug in combination, and 4) unoccluded. Each condition was replicated three times before going on to the next. Devices were refit prior to each replication with the following exception. Conditions 2 and 3 were tested as a pair. First the plug was fit and tested. The muff was then fit without removing the plug, and the two devices were tested in combination. All fits were made by the same experimenter (P.O.). Within each ear by replication condition, the set of thirty-three third-octave measurements were made in parallel using broadband noise, first with microphone in the flat frequency response mode followed by the diffuse-field equalization mode. These measurements were recorded using the Brüel and Kjaer spectrum analyzer and stored on disk.

Results

The mean sound level measurements, in dB SPL, are shown in Tables 1-4 for the thirty-three third octave bands tested, averaged over the three replications for each of the four ear conditions. Data are presented separately for the two settings of the measurement microphone (diffuse-field equalization and flat frequency response) and the two tests (Test 1 and Test 2) that were conducted four months apart. As indicated by the standard deviations (for the most part less than 2 dB), there was virtually no change in the measurements conducted during each test. Figures 3 and 4 show the sound level measurements, dB SPL, plotted as a function of frequency for each of the four ear conditions, for the two microphone settings, respectively. The data have been averaged across the two tests, as well as the three replications within test. A repeated measures analysis of variance (ANOVA, Daniel, 1983) applied to these data indicated that there were significant main effects of ear condition, microphone setting, and stimulus frequency ($p<0.0001$), as well as a number of significant interactions including frequency by test, ear condition by microphone setting, ear condition by frequency, microphone setting by frequency, ear condition by frequency by test, ear by microphone setting by frequency and ear by microphone setting by frequency by test ($p<0.01$ or better).

Averaged across frequencies and microphone settings, sound levels were highest in the unoccluded condition (82.9 dB SPL), followed by the muff (56.9 dB SPL), plug (45.3 dB SPL) and muff and plug in combination (37.7 dB SPL). The difference in the sound level measurements due to the test date was generally no greater than 6 dB for any of the eight combinations of ear condition and microphone setting. Exceptions in the order of 7-10 dB were noted at 12.5 Hz for the muff, plug, and muff and plug conditions, at 100 Hz for the muff and plug condition, and at 8 kHz, 12.5 kHz, 16 kHz and 20 kHz for the muff condition. Averaged across tests and frequencies, sound level measurements were 4 dB less with the diffuse-field equalization compared with the flat frequency response setting of the microphone for each of the four ear conditions. Averaged across tests and ear conditions, the difference was no greater than 1 dB below 500 Hz. It increased monotonically from 2-15 dB from 500 Hz to 2.5 kHz and then decreased monotonically from 11-4 dB from 4 kHz-20 kHz. The results for the two microphone settings are compared for each ear condition in Figure 5. It can be seen that the configurations of the functions relating sound pressure level and frequency were highly similar.

Ambient noise levels for one-third octave bands from 12.5 Hz to 20 kHz measured with microphone in each of the two modes are given for reference in Annex B. Except for five frequency bands in the range of 31.5 Hz to 80 Hz, these were less than 20 dB SPL for both the unoccluded and protected conditions. At all but 63 Hz, ambient levels were at least 15 dB below the sound pressure level measurements made for the stimulus.

Mean insertion loss measurements are shown in Tables 5-8 for the thirty-three third octave bands tested, averaged over the three replications, for each of the four ear conditions. Insertion loss values were obtained by taking the difference between unoccluded and protected sound levels. As in the case of the sound level measurements, data are presented separately for the two settings of the measurement microphone (diffuse-field equalization and flat frequency response) and the two tests (Test 1 and Test 2). A repeated measures ANOVA applied to these data showed statistically significant main effects of test ($p<0.05$), ear condition ($p<0.0001$), and frequency ($p<0.0001$) and a number of significant interactions including frequency by test, ear condition by microphone setting, ear condition by frequency, microphone setting by frequency, ear condition by frequency by test, ear condition by microphone setting by frequency, and ear condition by microphone setting by frequency by test ($p<0.02$ or better).

Averaged across ear conditions, microphone settings and frequencies, the difference due to test was 2 dB. For the ninety-nine combinations of ear condition and frequency, differences in insertion loss measured during the two tests were no greater than 5 dB, exception in nine instances (two in the muff condition, two in the plug condition, and five in the muff and plug condition), in which they ranged from 6-9 dB. These outliers were observed in the frequency regions below 500 Hz and above 6.3 kHz. Figure 6 shows a comparison of insertion loss values as a function of frequency, for the two microphone settings, separately for each of the three protector conditions. The data have been averaged across tests. As can be seen, there was virtually no difference due to the microphone setting. A comparison of the insertion loss observed for the muff, plug, and muff and plug in combination, averaged across microphone settings, is presented in Figure 7. For the muff, insertion loss was fairly constant at 12 dB from 12.5 Hz to 125 Hz, increased from 14.4 dB at 160 Hz to 38.5 dB at 630 Hz, and then remained fairly constant at 35 dB from 800 Hz to 20 kHz. In contrast, for the plug insertion loss increased monotonically from 6.1 dB at 12.5 Hz to 52.7 dB at 630 Hz, remained constant at 51.5 dB up to 2.5 kHz, increased to 58.5 dB at 8 kHz, and then decreased to 43.5 dB at 20 kHz. With the muff and plug in combination, insertion loss increased monotonically from 11.28 dB at 12.5 Hz to 61.83 dB SPL at 400 Hz and then remained at approximately 57.17 dB up to 20 kHz. For all intents and purposes, it appears that, regardless of the protector condition, there was little change in insertion loss beyond 630 Hz. Below this frequency, the muff and plug in combination provided as much as 20 dB more sound reduction than the muff alone and as much as 15 dB more sound reduction than the plug alone. At higher frequencies, the outcomes for the muff and plug in combination were highly similar to those observed for the plug alone. For either of these conditions, sound reduction was about 20 dB greater than that observed for the muff.

Discussion

This investigation was carried out to determine the validity of assessing the sound reduction afforded by hearing protectors using an existing acoustical test fixture that had been designed under contract for this purpose (Kunov et al., 1988; Kunov and Giguère, 1989). To this end, insertion loss values were calculated using sound level measurements made with the ear simulator of the ATF unoccluded or fitted with either a muff (E-A-R 3000), plug (E-A-R classic) or muff and plug in combination. The results indicated that the sound level measurements were highly repeatable both within and between test sessions. Across tests scheduled four months apart, differences were generally no greater than 6 dB. While the microphone setting did not affect insertion loss values, it was a significant determinate of the sound level measurements. Typically levels measured in the flat frequency response mode were greater than those measured with the diffuse-field equalization. Differences took the form of a U-shaped function over the range of frequencies investigated, and were of the order of 6-15 dB from 1.25 kHz to 10 kHz, peaking at 2.5 kHz. Based on specifications provided by the manufacturer, the diffuse-field option was specifically designed for use with the Zwislocki coupler in KEMAR to provide spectrally correct recordings for loudspeakers. The differences observed match the manufacturer's specifications (see Annex A).

In order to determine the validity of using the ATF in place of human subjects for measuring the sound reduction capability for the muff and plug under review, insertion loss values observed in the current study were compared with REAT measurements published by the manufacturer (the specification) and an independent research group (Abel et al., 1992). For the manufacturer's specification, data were available for third octave bands from 125 Hz to 8 kHz and for the laboratory study, from 500 Hz to 8 kHz. The findings are presented in Table 9 and Figure 8. Standard deviations associated with the REAT means shown were less than 5 dB for the muff and 8 dB or less for the plug and muff and plug in combination**.** For the muff, the insertion loss and attenuation values (averaged for the two sets of REAT measurements) were within 4 dB, except at 500 Hz and 1 kHz where the IL values overestimated and underestimated the REAT data by 8 dB and 7 dB respectively. In the case of the plug, the insertion loss values overestimated the REAT data by 8-18 dB at all but 125 Hz and 250 Hz where IL values underestimated the REAT data by 10 dB and 4 dB, respectively. Although manufacturer's specifications were not available for the muff and plug in combination, a comparison could be made with published laboratory data (Abel et al., 1992). As shown in the Table 9, IL values were 17-18 dB greater than the REAT measurements at 2 kHz, 6.3 kHz and 8 kHz and 6-7 dB greater at 500 Hz, 1 kHz and 4 kHz. These analyses appear to suggest that the ATF might provide a reasonable estimate of REAT data in the case of a muff but not a plug or muff and plug in combination.

The comparisons of IL values and REAT data presented above fail to take into consideration the limiting effects of bone conduction in the human head and the perceptual masking effects of physiological noise at low frequencies. The following equation proposed by Schroeter and Poesselt (1986) and later evaluated by Giguère and Kunov (1989) takes these factors into account in correcting IL:

$$IL_c(f) = 20 \log \left(10^{-IL(f)/20} + 10^{-[MAFB(f) - MAF(f)] - OE(f)]/20}\right) + PM(f), \qquad (1)$$

where, $IL_c(f)$ is the corrected insertion loss, $IL(f)$ is the measured insertion loss, MAFB(f) – MAF(f) is the level difference between the minimum audible field via bone conduction and the minimum audible field via air-conduction, $OE(f)$ is the occlusion effect of the hearing protector in dB, $PM(f)$ is the physiological masking that would apply for REAT measurements in dB, and f is the frequency in Hz. Details are given in Giguère and Kunov (1989).

Comparison of the observed and corrected values of IL in Table 9 indicates that there was virtually no change for the muff. However, substantial decreases in IL were noted for the plug. The difference between the corrected IL values and the average of the previously published REAT by the manufacturer and Abel et al. (1992) were equal to or less than 5 dB in the range of 500 Hz to 8 kHz. The corrected IL underestimated the REAT data by 14 dB at 125 Hz and by 9 dB at 250 Hz. Giguère and Kunov (1989) reached a similar conclusion, although the match between the two methods was closer in the present study.

Conclusions

The results of this investigation indicate that insertion loss measurements made using the DRDC Toronto ATF, corrected for bone conduction, occlusion effects and low-frequency masking correspond well with real-ear at threshold values for an earmuff in the range of 125 Hz to 8 kHz or an earplug in the range of 500 Hz to 8 kHz, for the average Caucasian male ear. Although insertion loss values were not affected by the mode of operation of the Etymotic microphone, sound level measurements differed by as much as 15 dB at mid-frequencies, in line with the manufacturer's specifications. As suggested by the manufacturer, the diffuse-field mode is recommended in cases where ATF recordings will be used with headphones. The free-field mode provides the best estimate of the level at the eardrum.

References

Abel, S.M. and Armstrong, N.M. (1992). “The combined sound attenuation of earplugs and earmuffs.” Appl. Acoust. 36, 19-30.

Abel, S.M., Rockley, T., Goldfarb, D. and Hawke, M. (1990). "External ear canal shape and its relation to the effectiveness of sound attenuating earplugs." J. Otolaryngol. 19(2), 91-95.

Abel, S.M., Sass-Kortsak, A. and Kielar, A. (2002). “The effect on earmuff attenuation of other safety gear worn in combination.” Noise & Health 5, 1-13.

Berger, E.H. (2000). “Hearing protection devices,” in Royster, L.H., Royster, D.P., Driscall, D.P. and Layne, M., eds. The Noise Manuel, 5th ed., American Industrial Hygiene Assoc., Fairfax, VA., pp. 379-454.

Burkhard, M.D. and Sachs, R.M. (1975). “Anthropmetric manikin for acoustic research.” J. Acoust. Soc. Am. 58(1), 214-222.

Crabtree, R.B. (1992). “Application of an acoustic manikin to the study of continuous and impulsive noise exposure.” Proceedings of Inter-noise 92, Toronto, ON, July 20-22, 1992.

CSA Z94.2-02 (2002). “Hearing protection devices – performance, selection, care, and use.” Canadian Standards Association, Rexdale, ON.

Daniel, W.W. (1983). Biostatistics: A Foundation for Analysis in the Health Sciences, 3rd ed. New York, Wiley.

Giguère, C. (1986). “An acousto-mechanical model of the hearing system with applications for hearing protection.” Unpublished MA.Sc. thesis, Depts. of Electrical and Biomedical Engineering, University of Toronto.

Giguère, C. and Kunov, H. (1989). “An acoustic head simulator for hearing protector evaluation. II. Measurements in steady-state and impulse noise environments.” J. Acoust. Soc. Am. 85(3), 1197-1205.

Kunov, H. and Giguère, H. (1989). “An acoustic head simulator for hearing protector evaluation. I. Design and construction.” J. Acoust. Soc. Am. 85(3), 1191-1196.

Kunov, H., Racansky, D. and Ing, A. (1988). “Simulated intra-aural skin for an artificial ear.” Contract Report No. W7711-6-9280/01-SE, DCIEM, Toronto, Canada

Riko, K. and Alberti, P.W. (1982). “How ear protectors fail: A practical guide,” in Personal Hearing Protection in Industry, edited by P.W. Alberti (Raven, New York), pp. 323-338.

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Figures

Figure 1
The DRDC Toronto head simulator and speaker array.

Figure 2
The DRDC Toronto head simulator. View of the instrumented interior.

Figure 3
Sound level measurements obtained using the ATF (right ear), and Etymotic ER-11 1/2 inch microphone in the diffuse-field equalization mode. Results are presented for the four ear conditions, averaged across Tests 1 and 2.

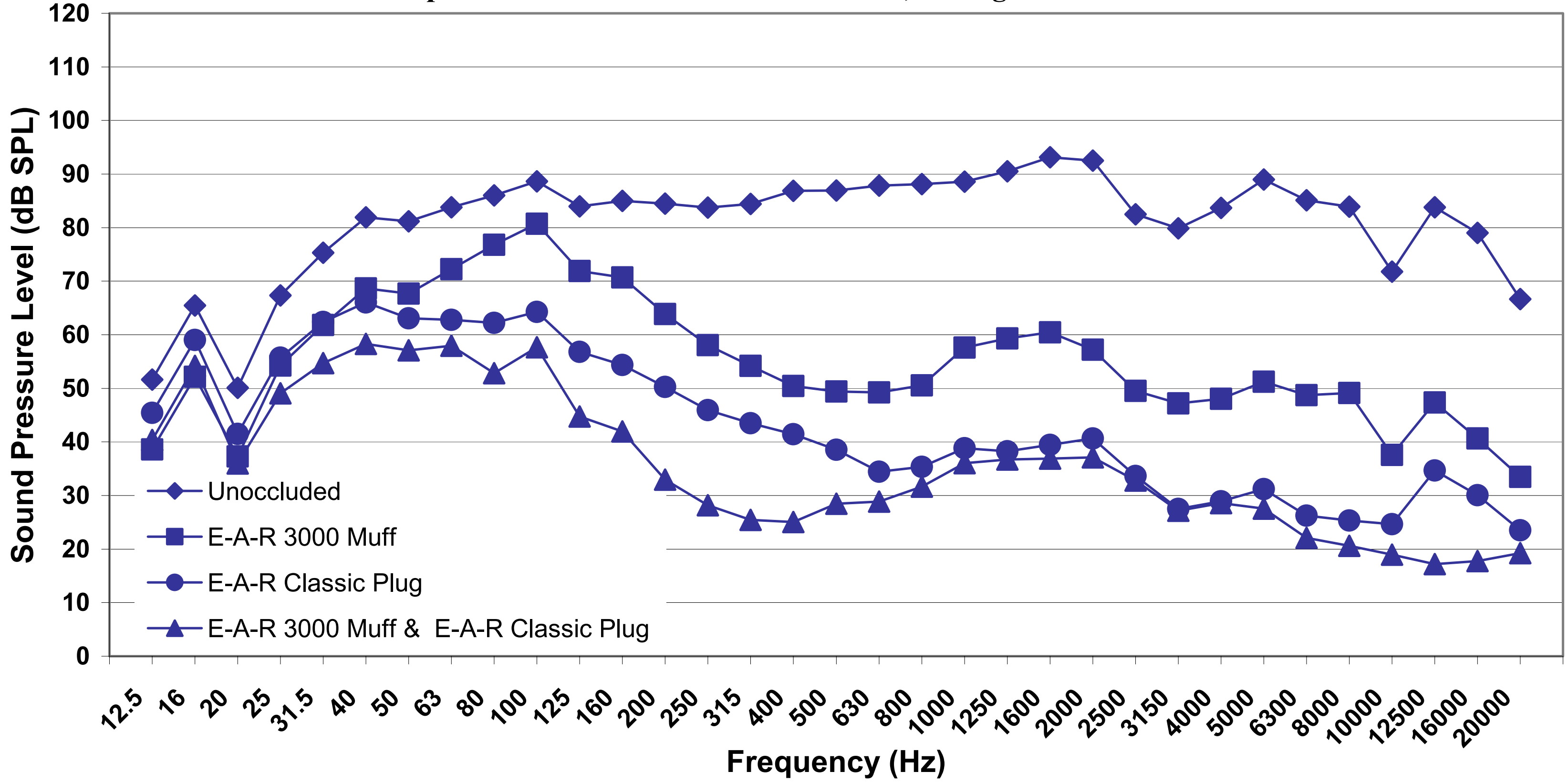


Figure 4
Sound level measurements obtained using the ATF (right ear), and Etymotic ER-11 1/2 inch microphone in the flat frequency mode. Results are presented for the four ear conditions, averaged across Tests 1 and 2.

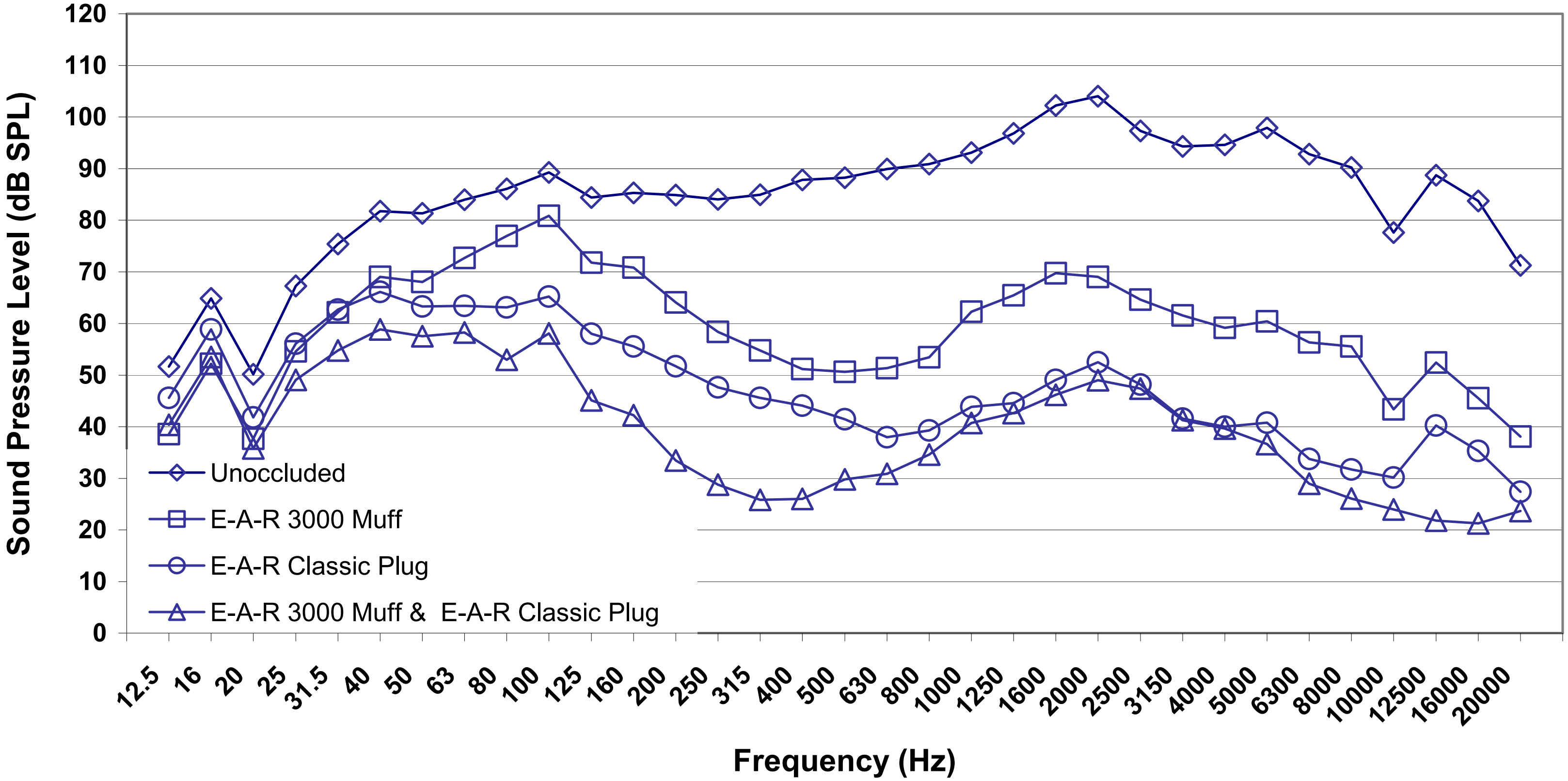


Figure 5
A comparison of sound level measurements obtained with the Etymotic ER-11 microphone in the diffuse-field equalization and flat frequency response modes, averaged across the two tests. Results are presented separately for the four ear conditions.

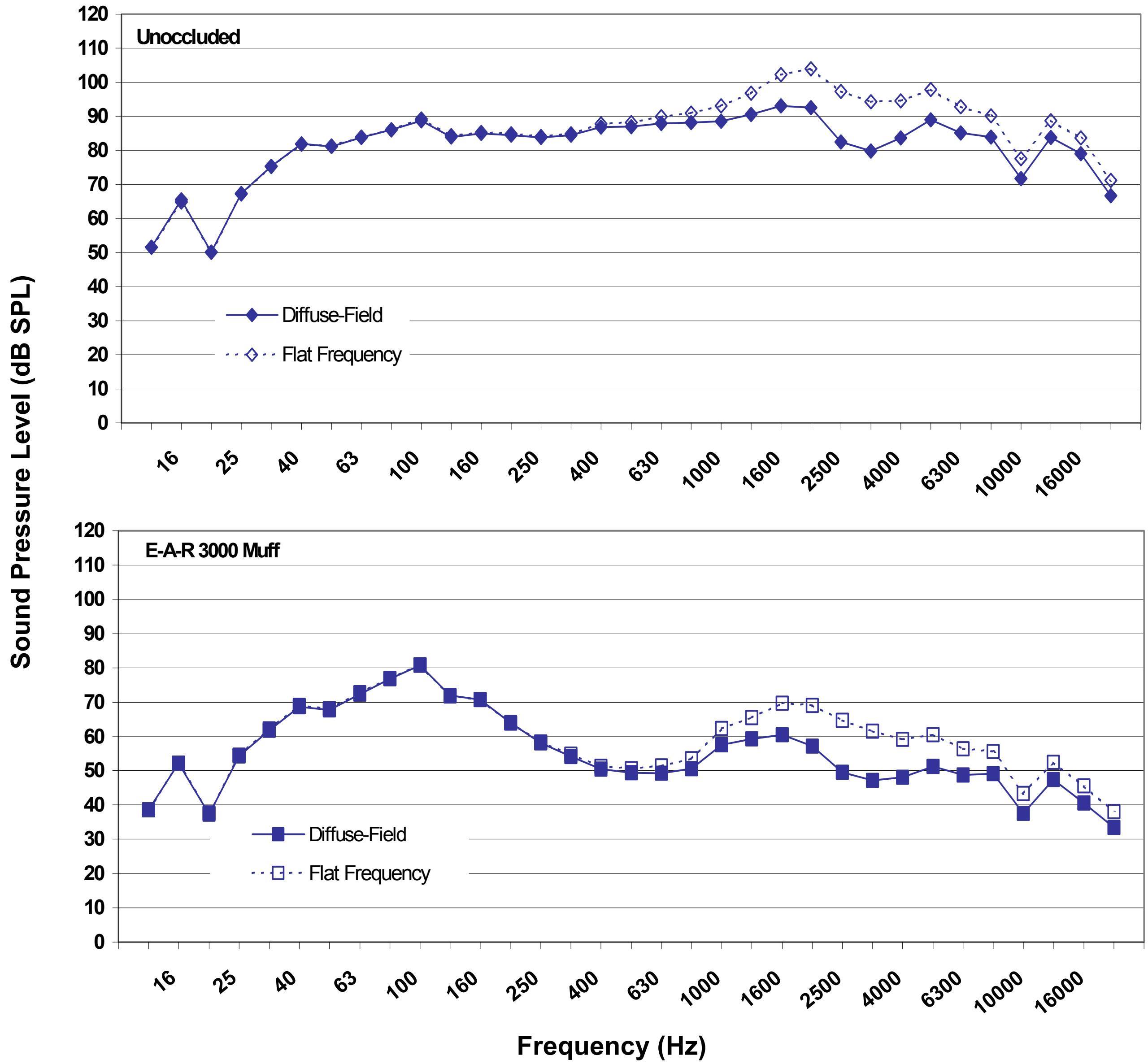


Figure 5 (cont'd)

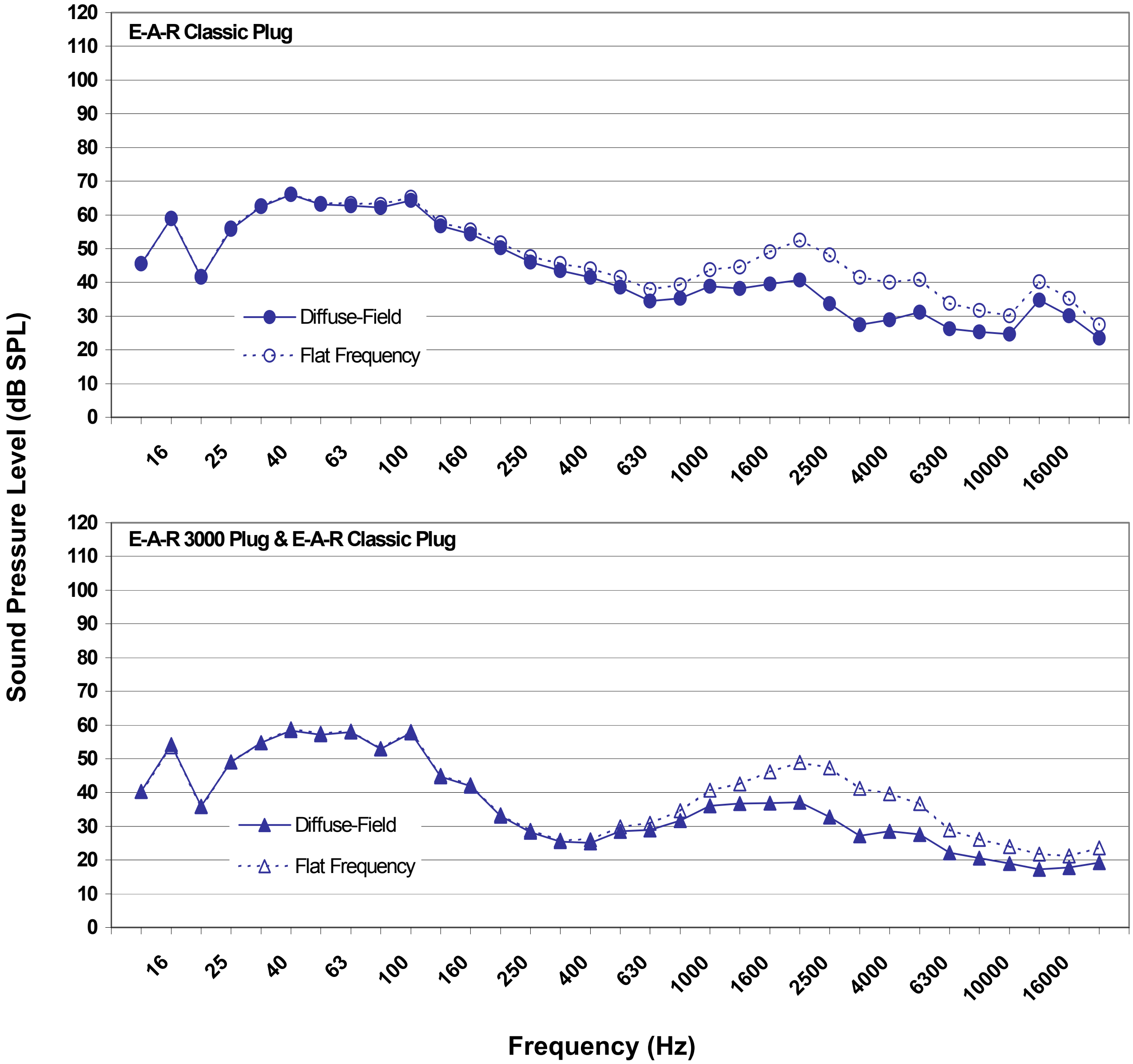


Figure 6
A comparison of insertion loss values obtained with the Etymotic ER-11 microphone in the diffuse-field equalization and flat frequency response modes, averaged across the two tests. Results are presented separately for the three protector conditions.

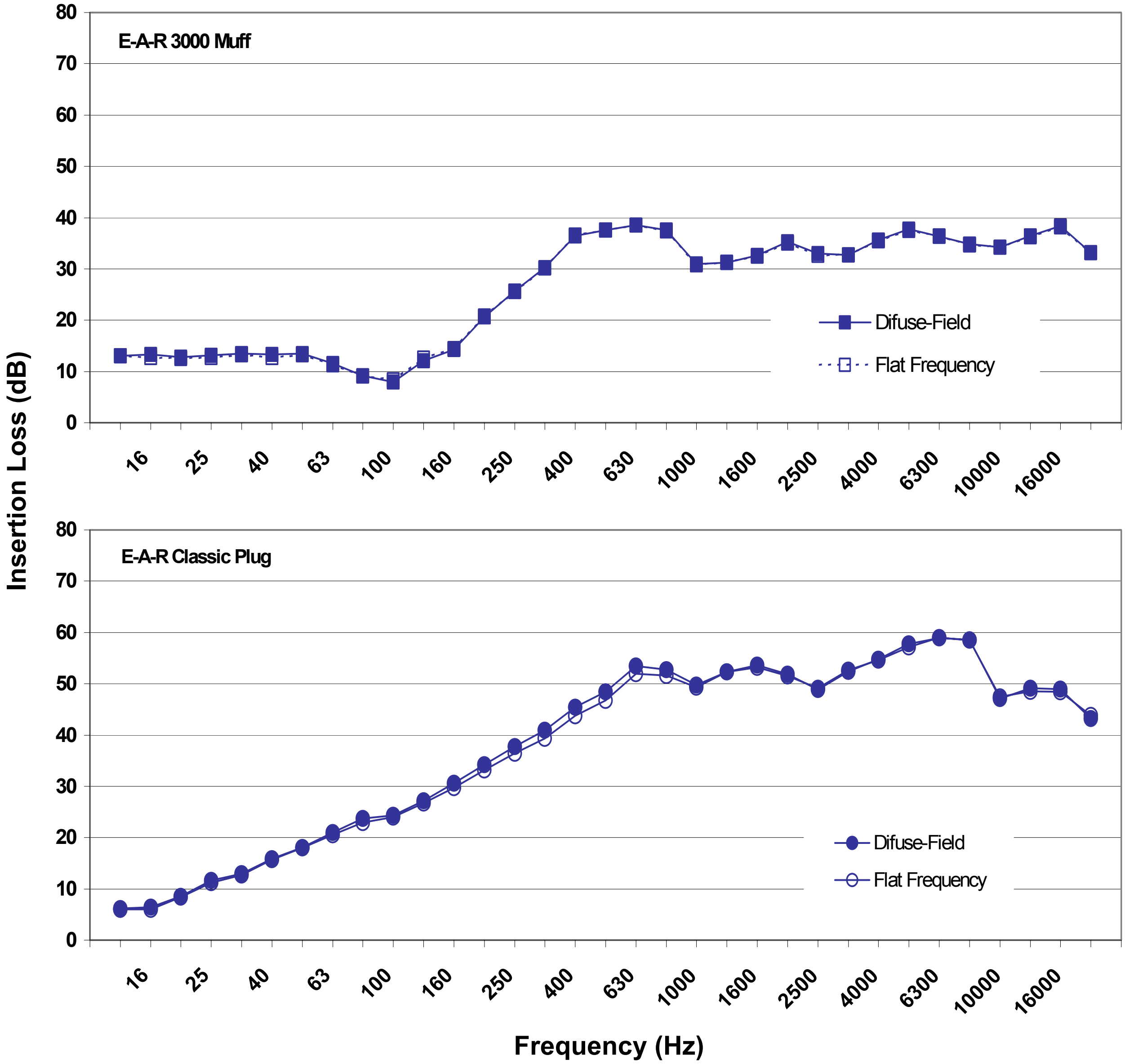


Figure 6 (cont'd)

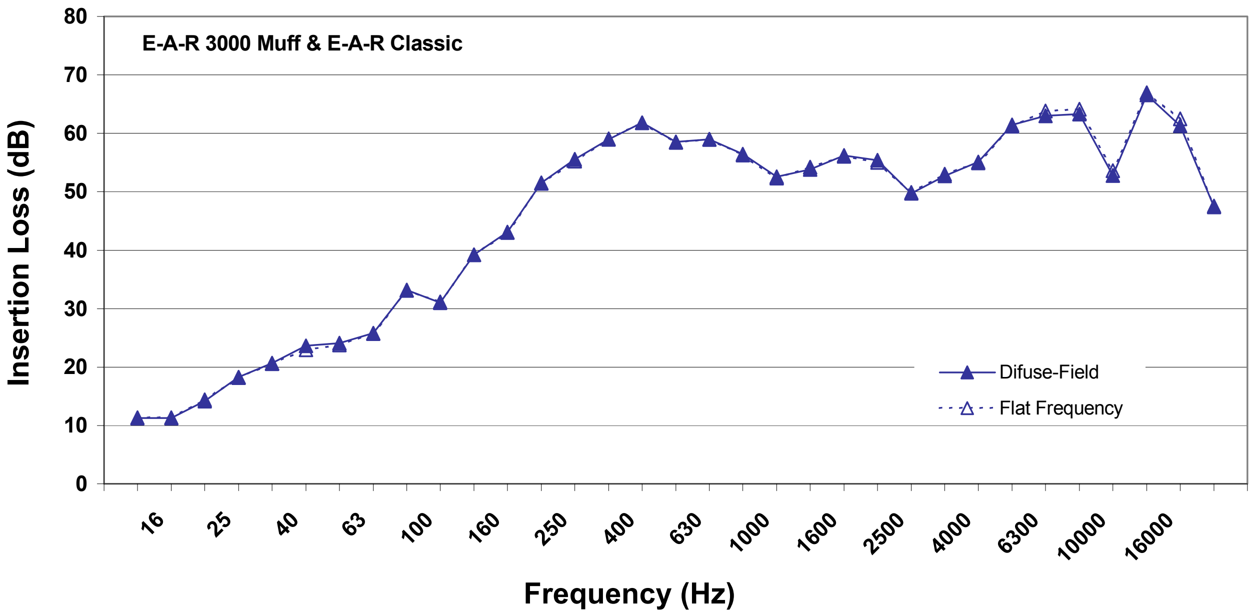


Figure 7
Insertion loss values obtained with the E-A-R 3000 muff, E-A-R Classic foam plug and muff and plug in combination. Results have been averaged across tests and microphone modes.

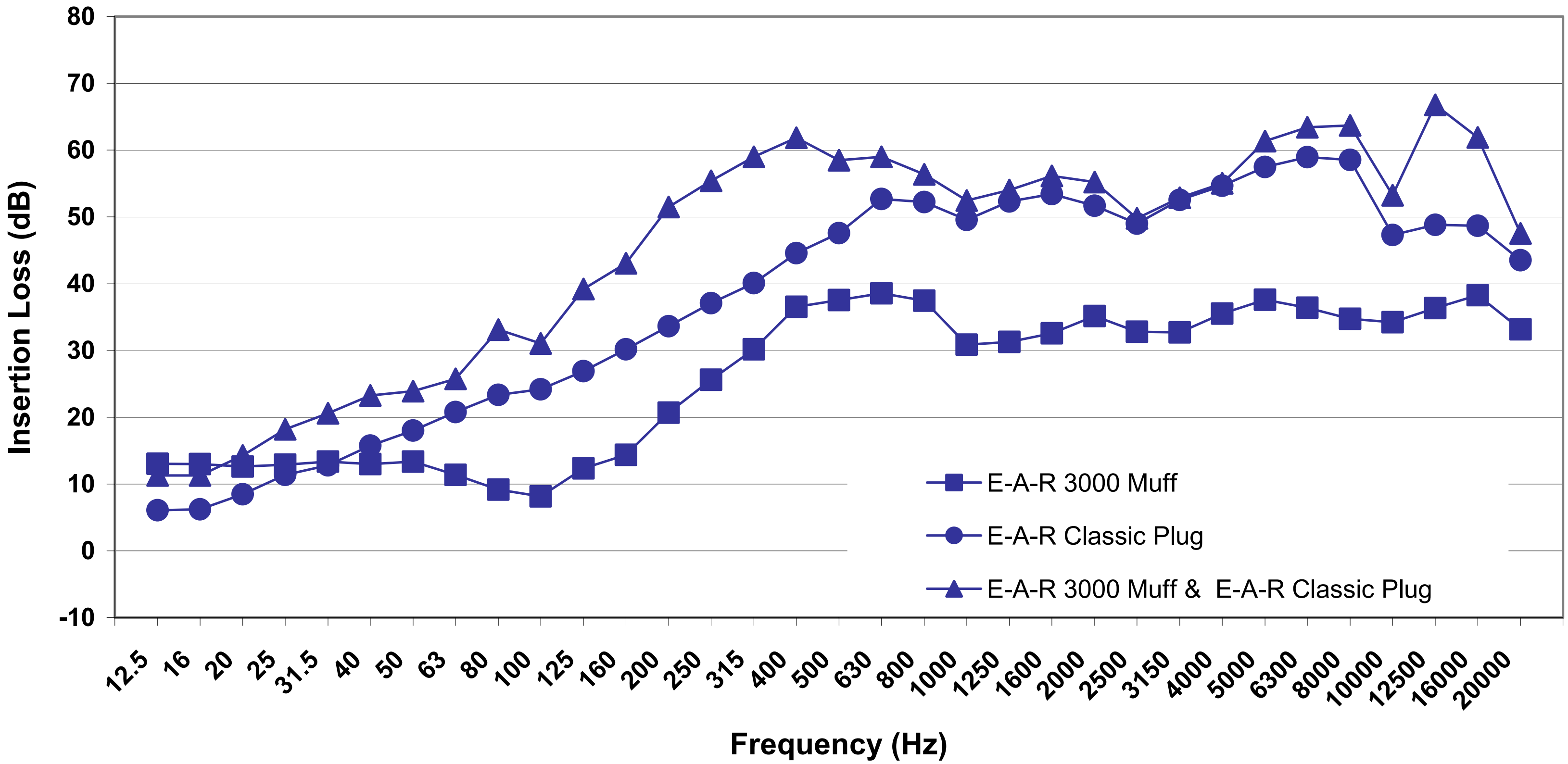
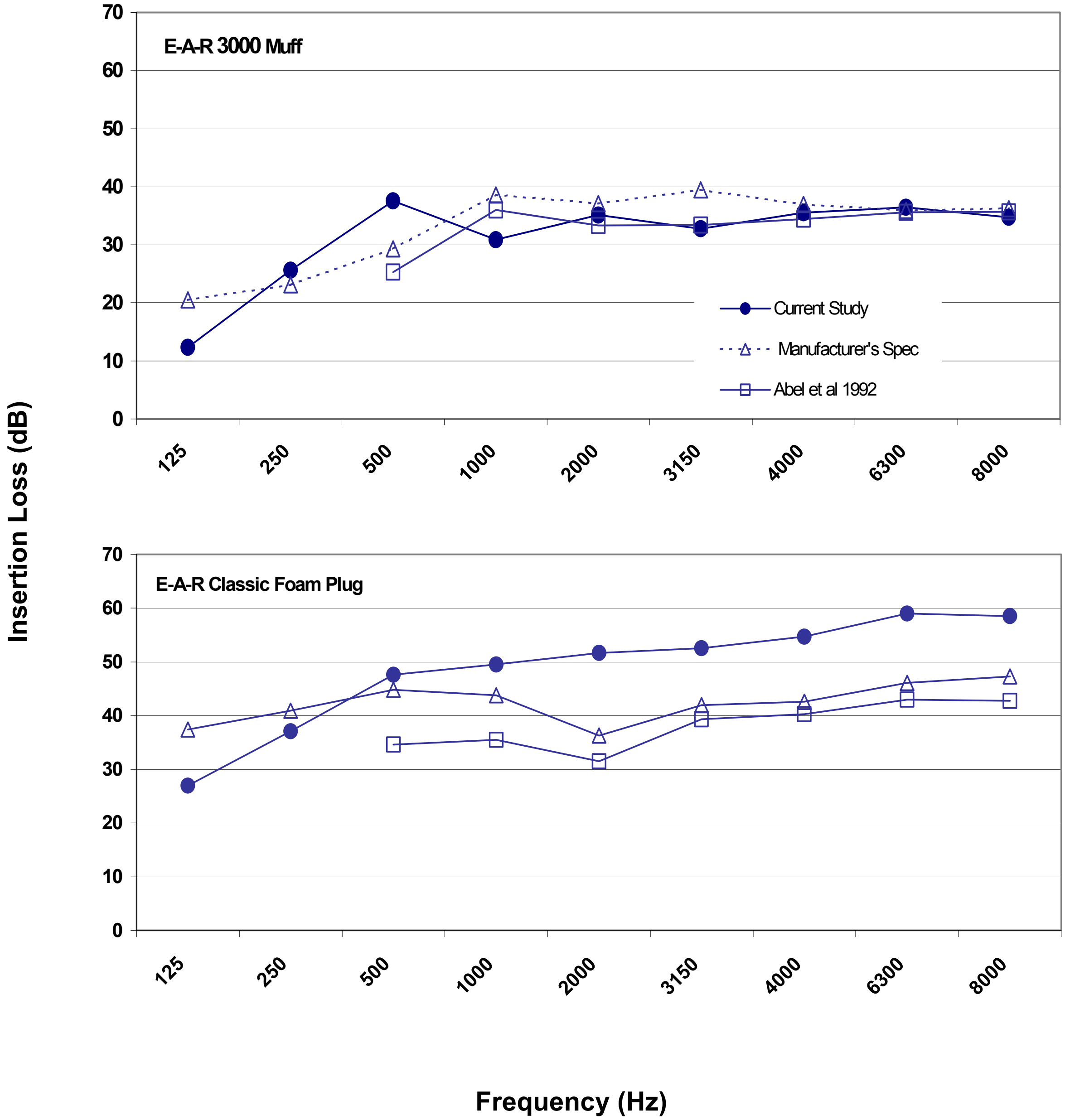


Figure 8
A comparison of mean insertion loss values obtained with the ATF and REAT data published by the manufacturer and an independent research laboratory. Results are presented for the E-A-R 3000 muff and E-A-R Classic plug.



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Tables

Table 1

Sound level measurements (dB SPL) obtained using the ATF (right ear*), unoccluded and fitted with the E-A-R 3000 muff, E-A-R Classic foam plug and muff and plug in combination, and Etymotic ER-11 microphone in the diffuse-field equalization mode.
Test 1

Freq (Hz)	Unoccluded	Muff	Plug	Muff & Plug
12.5	48.9 (0.4)**	33.7 (0.7)	41.8 (1.5)	36.2 (2.0)
16	64.3 (0.3)	49.3 (1.0)	57.5 (1.7)	51.5 (1.8)
20	49.8 (0.3)	35.4 (0.6)	40.3 (1.8)	34.4 (1.5)
25	68.5 (0.8)	54.4 (0.5)	56.3 (2.1)	49.5 (1.1)
31.5	75.4 (0.4)	61.2 (0.8)	62.0 (2.1)	54.4 (1.2)
40	82.2 (0.2)	69.0 (0.3)	65.2 (2.6)	57.8 (0.5)
50	80.4 (0.1)	67.1 (0.4)	61.6 (2.8)	55.3 (0.5)
63	83.1 (0.5)	72.7 (0.7)	60.6 (3.2)	56.1 (1.3)
80	85.3 (0.2)	77.2 (0.2)	59.5 (4.4)	50.6 (4.3)
100	88.9 (0.3)	79.9 (0.4)	62.7 (4.1)	54.1 (5.6)
125	83.8 (0.0)	70.8 (0.9)	55.1 (4.0)	43.2 (7.2)
160	85.5 (0.1)	69.8 (0.2)	53.4 (4.0)	40.7 (5.0)
200	84.8 (0.1)	63.6 (0.3)	49.8 (4.1)	31.9 (3.2)
250	84.9 (0.2)	58.0 (0.4)	45.8 (3.8)	25.3 (1.8)
315	85.2 (0.1)	53.8 (0.5)	42.4 (3.6)	23.7 (1.1)
400	88.2 (0.1)	49.7 (0.5)	40.1 (3.4)	22.8 (1.3)
500	87.4 (0.1)	49.0 (0.9)	36.4 (2.2)	26.2 (0.5)
630	88.3 (0.2)	51.2 (0.8)	33.1 (2.3)	30.5 (0.6)
800	87.8 (0.1)	51.0 (0.7)	33.8 (1.4)	31.8 (0.4)
1000	88.1 (0.1)	57.5 (0.6)	38.4 (0.4)	36.1 (0.6)
1250	90.4 (0.1)	58.4 (0.7)	37.7 (0.4)	36.8 (0.4)
1600	93.1 (0.1)	59.5 (0.6)	39.3 (0.5)	37.3 (0.1)
2000	92.6 (0.1)	56.2 (0.9)	40.8 (0.5)	37.4 (0.2)
2500	82.7 (0.1)	47.5 (0.8)	34.2 (0.4)	33.5 (0.3)
3150	80.5 (0.1)	45.4 (0.2)	27.7 (0.5)	27.4 (0.2)
4000	84.9 (0.0)	47.2 (0.3)	28.8 (0.1)	28.6 (0.2)
5000	90.2 (0.1)	51.8 (0.5)	30.5 (1.0)	27.6 (0.1)
6300	86.1 (0.0)	51.5 (0.4)	25.4 (1.6)	21.9 (0.2)
8000	86.5 (0.1)	52.9 (0.5)	24.1 (1.8)	19.8 (0.3)
10000	73.7 (0.1)	39.0 (0.5)	23.1 (1.5)	16.2 (0.1)
12500	85.1 (0.1)	51.2 (1.7)	33.7 (1.3)	16.2 (0.2)
16000	79.5 (0.1)	44.6 (1.6)	28.5 (1.4)	15.8 (0.3)
20000	66.5 (0.1)	37.8 (4.0)	22.0 (1.7)	19.6 (1.0)

* Left ear blocked using the E-A-R Classic plug
** Mean (SD), N = 3

Table 2

Sound level measurements (dB SPL) obtained using the ATF (right ear*), unoccluded and fitted with the E-A-R 3000 muff, E-A-R Classic foam plug and muff and plug in combination, and Etymotic ER-11 microphone in the flat frequency response mode.

Test 1

Freq (Hz)	Unoccluded	Muff	Plug	Muff & Plug
12.5	48.7 (0.7)**	34.1 (0.8)	42.0 (0.9)	35.9 (1.6)
16	63.7 (0.8)	49.3 (0.3)	57.2 (1.8)	50.5 (1.6)
20	49.8 (0.2)	35.9 (0.4)	40.7 (1.2)	34.1 (1.7)
25	68.7 (0.2)	54.9 (0.5)	56.7 (1.5)	49.7 (1.4)
31.5	75.7 (0.2)	61.7 (0.6)	62.2 (1.7)	54.5 (1.1)
40	81.9 (0.1)	69.4 (0.8)	65.8 (2.0)	58.5 (0.6)
50	80.6 (0.3)	67.4 (0.3)	62.1 (2.4)	55.9 (0.7)
63	83.3 (0.2)	72.8 (0.6)	61.6 (2.9)	56.4 (0.9)
80	85.3 (0.1)	77.4 (0.2)	61.1 (3.5)	50.7 (4.5)
100	89.2 (0.2)	80.2 (0.2)	64.2 (3.2)	54.6 (6.0)
125	84.0 (0.1)	70.4 (1.0)	56.5 (3.3)	43.7 (7.3)
160	85.5 (0.1)	69.8 (0.2)	54.9 (3.5)	41.1 (4.9)
200	85.1 (0.1)	63.6 (0.2)	51.6 (3.3)	32.4 (3.1)
250	85.2 (0.0)	58.4 (0.2)	47.9 (3.2)	26.0 (2.1)
315	85.8 (0.0)	54.3 (0.5)	44.9 (3.3)	24.2 (0.9)
400	89.0 (0.1)	50.4 (0.4)	43.3 (3.1)	23.7 (1.4)
500	88.6 (0.1)	50.2 (1.0)	39.9 (2.6)	27.5 (0.4)
630	90.4 (0.1)	53.3 (0.8)	36.9 (2.8)	32.5 (0.6)
800	90.5 (0.1)	53.9 (0.8)	37.7 (1.9)	34.8 (0.4)
1000	92.6 (0.1)	62.2 (0.6)	43.3 (0.4)	40.8 (0.4)
1250	96.7 (0.1)	64.3 (0.6)	44.0 (0.6)	42.8 (0.3)
1600	102.3 (0.0)	68.7 (0.6)	48.9 (0.4)	46.6 (0.2)
2000	104.3 (0.1)	67.7 (0.9)	52.6 (0.3)	49.2 (0.3)
2500	97.6 (0.0)	62.4 (0.8)	48.8 (0.4)	48.2 (0.4)
3150	94.9 (0.1)	59.5 (0.2)	41.9 (0.4)	41.7 (0.2)
4000	95.8 (0.0)	58.3 (0.3)	40.0 (0.2)	39.8 (0.2)
5000	99.1 (0.0)	60.8 (0.3)	40.3 (1.1)	36.7 (0.2)
6300	93.8 (0.1)	58.9 (0.4)	33.2 (1.9)	29.2 (0.2)
8000	92.8 (0.0)	59.1 (0.4)	30.7 (2.0)	25.8 (0.3)
10000	79.5 (0.1)	44.6 (0.6)	29.0 (1.9)	21.3 (0.1)
12500	90.1 (0.1)	55.9 (1.7)	39.4 (1.5)	20.7 (0.2)
16000	84.3 (0.0)	49.3 (1.5)	34.1 (1.6)	20.0 (0.3)
20000	71.0 (0.1)	42.4 (3.4)	26.2 (1.8)	23.8 (1.1)

* Left ear blocked using the E-A-R Classic plug
** Mean (SD), N = 3

Table 3

Sound level measurements (dB SPL) obtained using the ATF (right ear*), unoccluded and fitted with the E-A-R 3000 muff, E-A-R Classic foam plug and muff and plug in combination, and Etymotic ER-11 microphone in the diffuse-field equalization mode. Test 2

Freq (Hz)	Unoccluded	Muff	Plug	Muff & Plug
12.5	54.3 (0.5)**	43.5 (6.4)	49.1 (0.1)	44.5 (1.6)
16	66.6 (0.7)	55.0 (5.9)	60.6 (0.8)	56.9 (1.9)
20	50.4 (0.6)	39.1 (5.2)	42.7 (0.5)	37.5 (1.7)
25	66.2 (0.1)	54.1 (4.9)	55.2 (0.2)	48.6 (1.3)
31.5	75.2 (0.1)	62.5 (4.8)	62.8 (0.5)	55.0 (1.4)
40	81.7 (0.4)	68.2 (3.1)	66.8 (0.8)	58.8 (0.8)
50	81.9 (0.2)	68.3 (2.4)	64.6 (0.4)	58.9 (0.8)
63	84.5 (0.1)	71.8 (0.6)	64.9 (0.8)	59.8 (1.6)
80	86.7 (0.2)	76.4 (1.0)	64.9 (0.6)	55.1 (3.0)
100	88.4 (0.4)	81.5 (0.9)	65.9 (1.3)	61.2 (4.1)
125	84.1 (0.3)	73.0 (0.4)	58.5 (1.8)	46.3 (2.5)
160	84.6 (0.1)	71.6 (0.2)	55.3 (2.1)	43.1 (3.8)
200	84.1 (0.2)	64.1 (1.7)	50.8 (2.5)	34.0 (3.8)
250	82.6 (0.2)	58.1 (2.2)	46.1 (3.4)	31.1 (3.5)
315	83.6 (0.0)	54.6 (2.2)	44.7 (4.3)	27.2 (2.5)
400	85.5 (0.1)	51.2 (1.5)	42.8 (5.2)	27.3 (2.9)
500	86.5 (0.0)	49.9 (3.2)	40.8 (4.8)	30.7 (2.4)
630	87.4 (0.2)	47.3 (3.0)	35.7 (5.7)	27.3 (0.8)
800	88.4 (0.1)	50.2 (4.4)	36.9 (4.4)	31.5 (0.2)
1000	89.1 (0.0)	57.7 (3.6)	39.2 (2.1)	36.0 (0.3)
1250	90.7 (0.1)	60.3 (4.0)	38.8 (1.6)	36.6 (0.5)
1600	93.1 (0.0)	61.4 (3.7)	39.6 (1.8)	36.5 (0.3)
2000	92.4 (0.1)	58.2 (2.1)	40.5 (2.6)	36.9 (0.7)
2500	82.2 (0.1)	51.5 (3.0)	33.0 (0.8)	32.1 (1.2)
3150	79.2 (0.1)	49.0 (0.8)	27.3 (0.2)	26.9 (0.1)
4000	82.5 (0.1)	48.9 (2.5)	29.0 (1.4)	28.5 (0.2)
5000	87.8 (0.0)	50.6 (1.8)	31.9 (2.3)	27.5 (0.3)
6300	84.1 (0.1)	45.9 (1.4)	27.1 (1.9)	22.3 (0.2)
8000	81.4 (0.1)	45.3 (8.8)	26.5 (1.5)	21.5 (0.3)
10000	69.9 (0.1)	36.1 (9.5)	26.2 (2.3)	21.8 (0.5)
12500	82.5 (0.0)	43.5 (14.0)	35.7 (4.0)	18.2 (0.2)
16000	78.5 (0.1)	36.7 (15.3)	31.6 (3.0)	19.7 (0.3)
20000	66.9 (0.1)	29.2 (13.2)	25.0 (0.3)	18.9 (0.3)

* Left ear blocked using the E-A-R Classic plug

** Mean (SD), N = 3

Table 4

Sound level measurements (dB SPL) obtained using the ATF (right ear*), unoccluded and fitted with the E-A-R 3000 muff, E-A-R Classic foam plug and muff and plug in combination, and Etymotic ER-11 microphone in the flat frequency response mode.
Test 2

Freq (Hz)	Unoccluded	Muff	Plug	Muff & Plug
12.5	54.6 (0.4)**	43.0 (7.4)	49.2 (0.9)	44.8 (1.8)
16	66.0 (0.8)	55.0 (7.5)	60.5 (1.1)	56.6 (1.8)
20	50.5 (0.3)	39.4 (5.4)	42.9 (0.9)	37.4 (1.8)
25	65.8 (0.3)	54.2 (5.7)	55.5 (1.0)	48.5 (1.4)
31.5	75.0 (0.1)	62.6 (5.4)	63.2 (1.1)	55.0 (1.1)
40	81.6 (0.7)	68.7 (3.2)	66.4 (1.1)	59.2 (0.6)
50	82.0 (0.2)	68.7 (2.5)	64.6 (0.9)	59.1 (1.0)
63	84.6 (0.2)	72.6 (0.7)	65.2 (1.3)	60.0 (1.7)
80	86.8 (0.2)	76.5 (1.2)	65.2 (1.1)	55.3 (2.9)
100	89.3 (0.1)	81.5 (1.0)	66.3 (1.2)	61.6 (4.2)
125	84.8 (0.2)	73.1 (0.4)	58.9 (1.7)	46.5 (2.6)
160	85.0 (0.1)	71.7 (0.2)	56.2 (2.0)	43.4 (3.6)
200	84.6 (0.1)	64.5 (2.1)	51.8 (2.4)	34.5 (3.8)
250	82.8 (0.1)	58.4 (2.5)	47.3 (3.2)	31.6 (3.5)
315	84.0 (0.1)	55.2 (2.3)	46.3 (4.0)	27.5 (2.2)
400	86.6 (0.1)	52.0 (1.5)	44.9 (4.7)	28.3 (2.7)
500	87.8 (0.1)	51.0 (3.1)	43.1 (4.5)	32.1 (2.5)
630	89.4 (0.1)	49.4 (3.2)	39.0 (5.6)	29.2 (1.0)
800	91.3 (0.1)	53.1 (4.5)	40.8 (4.4)	34.4 (0.4)
1000	93.6 (0.0)	62.4 (3.6)	44.3 (2.1)	40.7 (0.2)
1250	97.0 (0.1)	66.6 (4.3)	45.2 (1.8)	42.5 (0.4)
1600	102.1 (0.1)	70.8 (4.0)	49.3 (2.1)	45.7 (0.4)
2000	103.7 (0.1)	70.2 (2.7)	52.4 (2.6)	48.8 (0.8)
2500	97.0 (0.1)	66.8 (3.6)	47.5 (0.9)	46.6 (1.2)
3150	93.6 (0.0)	63.6 (0.9)	41.2 (0.3)	40.9 (0.2)
4000	93.4 (0.1)	60.0 (2.6)	40.0 (1.5)	39.5 (0.2)
5000	96.7 (0.0)	60.1 (2.2)	41.3 (2.5)	36.6 (0.3)
6300	91.8 (0.0)	53.7 (1.4)	34.3 (2.0)	28.7 (0.2)
8000	87.6 (0.1)	52.0 (9.5)	32.7 (1.9)	26.4 (0.5)
10000	75.7 (0.1)	42.2 (9.8)	31.3 (2.5)	26.6 (0.6)
12500	87.3 (0.1)	49.0 (14.4)	41.0 (3.8)	22.9 (0.0)
16000	83.2 (0.1)	41.8 (15.8)	36.6 (2.8)	22.5 (0.4)
20000	71.5 (0.1)	33.8 (13.6)	28.6 (0.4)	23.5 (0.2)

* Left ear blocked using the E-A-R Classic plug
** Mean (SD), N = 3

Table 5

Insertion loss values (dB) for the E-A-R 3000 muff, E-A-R Classic foam plug and muff and plug in combination, obtained using the ATF (right ear*) and Etymotic ER-11 microphone in the diffuse-field equalization mode.
Test 1

Freq (Hz)	Muff	Plug	Muff & Plug
12.5	15.3 (0.8)**	7.1 (1.6)	12.7 (1.6)
16	15.0 (0.9)	6.8 (1.8)	12.8 (1.6)
20	14.3 (0.3)	9.4 (1.9)	15.3 (1.3)
25	14.1 (1.1)	12.2 (2.7)	18.9 (1.0)
31.5	14.2 (0.7)	13.5 (2.2)	21.0 (0.9)
40	13.1 (0.3)	16.9 (2.6)	24.4 (0.4)
50	13.3 (0.3)	18.8 (2.8)	25.1 (0.5)
63	10.4 (1.2)	22.4 (3.0)	27.0 (1.3)
80	8.1 (0.3)	25.7 (4.3)	34.7 (4.2)
100	9.0 (0.6)	26.2 (4.1)	34.8 (5.5)
125	13.0 (0.9)	28.7 (4.0)	40.6 (7.2)
160	15.6 (0.2)	32.1 (4.0)	44.7 (4.9)
200	21.2 (0.4)	35.0 (4.0)	52.9 (3.1)
250	26.9 (0.6)	39.1 (3.8)	59.6 (1.9)
315	31.4 (0.5)	42.9 (3.7)	61.5 (1.1)
400	38.6 (0.6)	48.1 (3.4)	65.4 (1.2)
500	38.4 (1.0)	51.0 (2.3)	61.2 (0.4)
630	37.1 (0.8)	55.2 (2.4)	57.8 (0.5)
800	36.8 (0.7)	54.0 (1.3)	56.0 (0.5)
1000	30.6 (0.7)	49.7 (0.4)	52.0 (0.6)
1250	32.0 (0.7)	52.7 (0.3)	53.5 (0.4)
1600	33.6 (0.7)	53.8 (0.5)	55.9 (0.1)
2000	36.4 (0.9)	51.9 (0.6)	55.3 (0.3)
2500	35.3 (0.8)	48.5 (0.4)	49.2 (0.3)
3150	35.2 (0.2)	52.8 (0.5)	53.1 (0.3)
4000	37.7 (0.3)	56.1 (0.1)	56.3 (0.2)
5000	38.3 (0.5)	59.7 (1.0)	62.6 (0.1)
6300	34.6 (0.4)	60.7 (1.6)	64.2 (0.2)
8000	33.6 (0.5)	62.3 (1.8)	66.7 (0.3)
10000	34.7 (0.5)	50.6 (1.5)	57.5 (0.1)
12500	33.9 (1.6)	51.5 (1.4)	69.0 (0.3)
16000	35.0 (1.6)	51.0 (1.4)	63.7 (0.3)
20000	28.7 (4.0)	44.5 (1.6)	46.9 (1.0)

* Left ear blocked using the E-A-R Classic plug
** Mean (SD), N = 3

Table 6

Insertion loss values (dB) for the E-A-R 3000 muff, E-A-R Classic foam plug and muff and plug in combination, obtained using the ATF (right ear*) and Etymotic ER-11 microphone in the flat frequency response mode. Test 1

Freq (Hz)	Muff	Plug	Muff & Plug
12.5	14.5 (1.4)**	6.6 (1.4)	12.8 (2.1)
16	14.4 (1.1)	6.5 (2.4)	13.2 (2.2)
20	13.9 (0.5)	9.1 (1.1)	15.7 (1.8)
25	13.7 (0.7)	12.0 (1.7)	19.0 (1.4)
31.5	14.1 (0.7)	13.6 (1.8)	21.3 (1.2)
40	12.6 (0.7)	16.1 (1.9)	23.4 (0.6)
50	13.3 (0.2)	18.6 (2.4)	24.7 (0.7)
63	10.5 (0.3)	21.7 (3.2)	26.9 (1.1)
80	7.9 (0.3)	24.2 (3.6)	34.6 (4.6)
100	9.0 (0.4)	25.0 (3.3)	34.6 (5.9)
125	13.6 (1.0)	27.5 (3.4)	40.3 (7.3)
160	15.7 (0.3)	30.7 (3.5)	44.5 (4.9)
200	21.5 (0.2)	33.5 (3.3)	52.7 (3.1)
250	26.8 (0.2)	37.3 (3.2)	59.2 (2.1)
315	31.5 (0.5)	40.9 (3.3)	61.6 (0.9)
400	38.6 (0.4)	45.8 (3.1)	65.4 (1.4)
500	38.4 (1.1)	48.7 (2.7)	61.1 (0.3)
630	37.1 (0.8)	53.5 (2.7)	57.9 (0.7)
800	36.6 (0.8)	52.8 (1.9)	55.8 (0.5)
1000	30.4 (0.7)	49.2 (0.4)	51.7 (0.4)
1250	32.4 (0.7)	52.7 (0.6)	53.9 (0.4)
1600	33.6 (0.6)	53.4 (0.4)	55.7 (0.2)
2000	36.5 (0.9)	51.7 (0.3)	55.1 (0.3)
2500	35.2 (0.8)	48.8 (0.4)	49.4 (0.4)
3150	35.4 (0.2)	53.0 (0.5)	53.3 (0.3)
4000	37.5 (0.3)	55.8 (0.2)	56.0 (0.2)
5000	38.3 (0.3)	58.8 (1.1)	62.4 (0.2)
6300	34.9 (0.4)	60.6 (1.8)	64.6 (0.2)
8000	33.7 (0.4)	62.1 (2.0)	67.0 (0.3)
10000	34.9 (0.6)	50.5 (1.9)	58.2 (0.0)
12500	34.2 (1.7)	50.7 (1.5)	69.4 (0.3)
16000	35.0 (1.5)	50.2 (1.6)	64.3 (0.3)
20000	28.5 (3.5)	44.8 (1.7)	47.1 (1.1)

* Left ear blocked using the E-A-R Classic plug
** Mean (SD), N = 3

Table 7

**Insertion loss values (dB) for the E-A-R 3000 muff,
E-A-R Classic foam plug and muff and plug in combination,
obtained using the ATF (right ear*) and
Etymotic ER-11 microphone in the diffuse-field equalization mode.
Test 2**

Freq (Hz)	Muff	Plug	Muff & Plug
12.5	10.8 (6.6)**	5.2 (0.5)	9.8 (1.2)
16	11.6 (6.4)	6.0 (0.8)	9.7 (1.5)
20	11.3 (5.6)	7.7 (0.4)	12.9 (1.3)
25	12.1 (4.9)	11.0 (0.2)	17.6 (1.3)
31.5	12.8 (4.8)	12.4 (0.5)	20.2 (1.4)
40	13.5 (3.4)	14.9 (1.2)	22.9 (0.9)
50	13.6 (2.4)	17.3 (0.6)	23.0 (0.8)
63	12.7 (0.6)	19.6 (0.7)	24.7 (1.5)
80	10.3 (1.1)	21.8 (0.4)	31.6 (2.8)
100	6.9 (1.0)	22.5 (1.7)	27.2 (4.5)
125	11.1 (0.5)	25.6 (1.9)	37.8 (2.6)
160	13.0 (0.2)	29.2 (2.1)	41.4 (3.8)
200	20.0 (1.8)	33.3 (2.4)	50.1 (3.7)
250	24.5 (2.4)	36.5 (3.4)	51.5 (3.5)
315	29.0 (2.2)	38.9 (4.3)	56.4 (2.5)
400	34.4 (1.4)	42.7 (5.2)	58.3 (2.9)
500	36.6 (3.2)	45.7 (4.8)	55.8 (2.4)
630	40.0 (3.2)	51.7 (5.6)	60.1 (0.8)
800	38.3 (4.5)	51.6 (4.3)	56.9 (0.3)
1000	31.4 (3.6)	49.9 (2.1)	53.1 (0.3)
1250	30.4 (3.9)	51.9 (1.6)	54.1 (0.4)
1600	31.7 (3.7)	53.5 (1.8)	56.6 (0.3)
2000	34.1 (2.0)	51.8 (2.6)	55.5 (0.6)
2500	30.7 (2.9)	49.2 (0.8)	50.2 (1.2)
3150	30.3 (0.8)	51.9 (0.2)	52.3 (0.1)
4000	33.5 (2.5)	53.5 (1.3)	53.9 (0.2)
5000	37.2 (1.8)	55.9 (2.3)	60.3 (0.3)
6300	38.2 (1.4)	57.0 (1.9)	61.8 (0.2)
8000	36.1 (8.7)	54.8 (1.5)	59.9 (0.3)
10000	33.8 (9.5)	43.7 (2.3)	48.2 (0.5)
12500	39.0 (14.0)	46.8 (4.0)	64.3 (0.2)
16000	41.8 (15.3)	46.9 (3.0)	58.8 (0.3)
20000	37.7 (13.2)	41.9 (0.3)	48.0 (0.3)

* Left ear blocked using the E-A-R Classic plug
** Mean (SD), N = 3

Table 8

Insertion loss values (dB) for the E-A-R 3000 muff, E-A-R Classic foam plug and muff and plug in combination, obtained using the ATF (right ear*) and Etymotic ER-11 microphone in the flat frequency response mode. Test 2

Freq (Hz)	Muff	Plug	Muff & Plug
12.5	11.6 (7.7)**	5.4 (1.4)	9.8 (2.1)
16	11.0 (7.3)	5.5 (1.9)	9.5 (2.7)
20	11.1 (5.5)	7.6 (1.1)	13.1 (2.0)
25	11.6 (5.6)	10.3 (1.1)	17.3 (1.7)
31.5	12.4 (5.3)	11.8 (1.2)	19.9 (1.1)
40	12.9 (3.9)	15.2 (1.8)	22.4 (1.1)
50	13.2 (2.7)	17.4 (0.9)	22.8 (0.8)
63	12.0 (0.6)	19.3 (1.4)	24.5 (1.6)
80	10.3 (1.3)	21.6 (1.0)	31.6 (3.0)
100	7.7 (1.0)	23.0 (1.2)	27.7 (4.3)
125	11.6 (0.6)	25.9 (1.7)	38.2 (2.4)
160	13.3 (0.2)	28.8 (2.0)	41.6 (3.6)
200	20.1 (2.2)	32.8 (2.3)	50.1 (3.7)
250	24.4 (2.5)	35.6 (3.3)	51.2 (3.5)
315	28.8 (2.3)	37.7 (4.0)	56.5 (2.2)
400	34.6 (1.5)	41.7 (4.7)	58.3 (2.6)
500	36.8 (3.1)	44.8 (4.5)	55.8 (2.5)
630	39.9 (3.2)	50.4 (5.6)	60.1 (1.1)
800	38.2 (4.4)	50.5 (4.5)	56.8 (0.4)
1000	31.2 (3.6)	49.3 (2.1)	52.9 (0.2)
1250	30.3 (4.3)	51.8 (1.8)	54.5 (0.4)
1600	31.3 (4.0)	52.9 (2.2)	56.4 (0.4)
2000	33.5 (2.8)	51.3 (2.5)	55.0 (0.8)
2500	30.1 (3.6)	49.4 (0.9)	50.4 (1.2)
3150	30.0 (0.9)	52.4 (0.3)	52.7 (0.2)
4000	33.3 (2.5)	53.4 (1.5)	53.9 (0.3)
5000	36.6 (2.2)	55.4 (2.5)	60.1 (0.3)
6300	38.1 (1.4)	57.5 (2.0)	63.1 (0.2)
8000	35.6 (9.5)	54.9 (1.9)	61.2 (0.6)
10000	33.5 (9.8)	44.4 (2.5)	49.1 (0.7)
12500	38.4 (14.4)	46.3 (3.8)	64.4 (0.1)
16000	41.4 (15.7)	46.6 (2.8)	60.6 (0.4)
20000	37.8 (13.7)	42.9 (0.4)	48.1 (0.2)

* Left ear blocked using the E-A-R Classic plug
** Mean (SD), N = 3

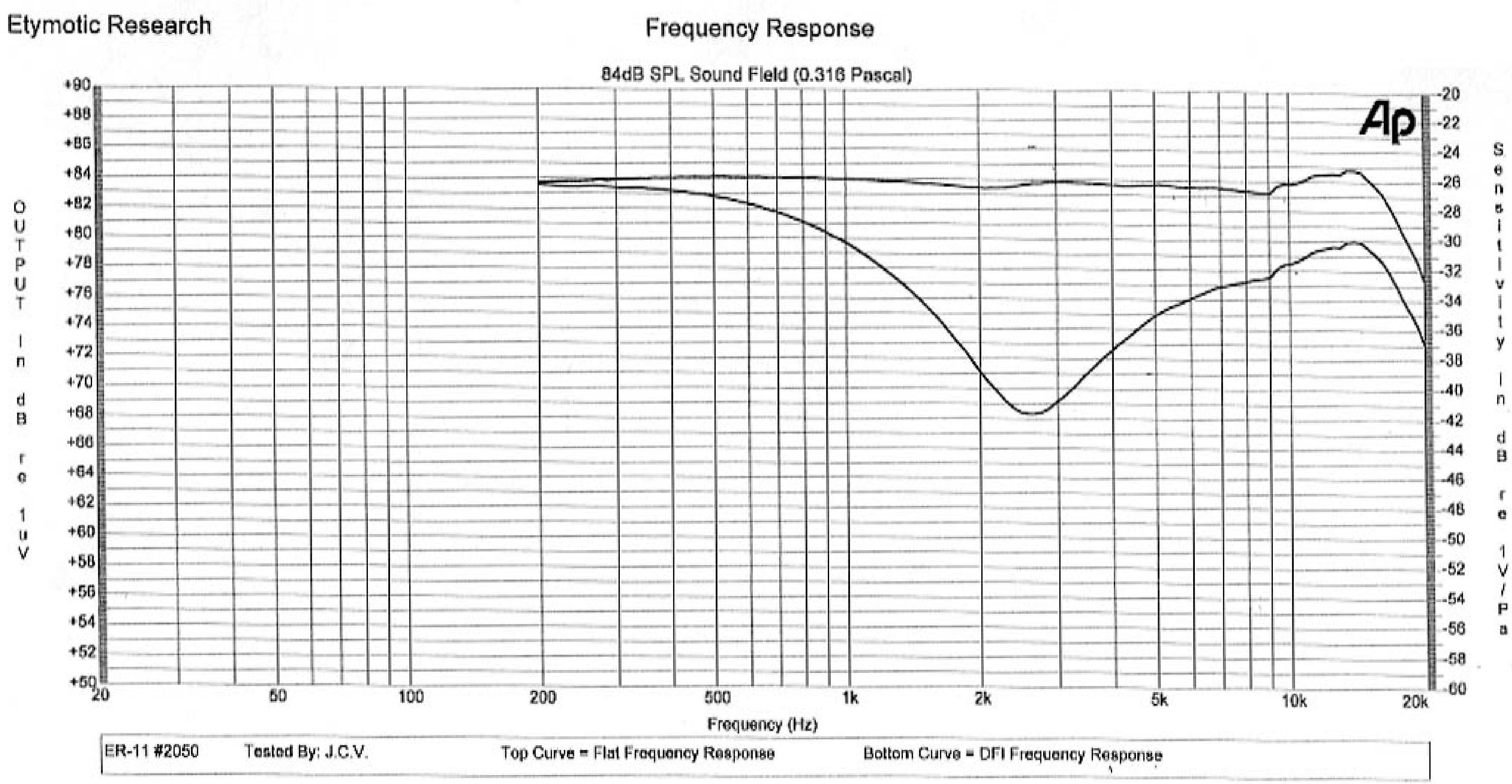
Table 9

Sound reduction afforded by the E-A-R 3000 muff, E-A-R Classic plug and muff and plug in combination: Observed and corrected insertion loss values in comparison with REAT data.

Freq (Hz)	Current Study IL (dB)	Manufacturer's Specification REAT (dB)	Abel et al. 1992	Corrected IL (dB)
Muff				
125	12.3	16.5	---	16.0
250	25.6	21.8	---	26.4
500	37.6	33.8	25.3	37.1
1000	30.9	40.4	36.0	29.8
2000	35.1	35.1	33.3	30.7
3150	32.7	36.2	33.4	31.2
4000	35.5	38.4	34.4	33.9
6300	36.4	38.3	35.6	34.5
8000	34.7	39.7	35.7	33.1
Plug				
125	26.9	37.4	---	22.5
250	37.1	40.9	---	31.5
500	47.6	44.8	34.6	40.8
1000	49.5	43.8	35.5	37.1
2000	51.7	36.3	31.5	39.3
3000	52.5	41.9	39.3	43.6
4000	54.7	42.6	40.3	45.7
6300	59.0	46.1	43.0	46.4
8000	58.5	47.3	42.7	46.2
Muff & Plug				
125	39.2	---	---	---
250	55.4	---	---	---
500	58.5	---	52.3	---
1000	52.4	---	45.5	---
2000	55.2	---	37.5	---
3150	52.9	---	45.9	---
4000	55.0	---	48.8	---
6300	63.4	---	46.6	---
8000	63.7	---	45.7	---

Annex A

Output of the Etymotic ER-11 microphone with diffuse-field equalization and flat frequency response settings. Published specifications



Etymotic Research
Frequency Response
84dB SPL Sound Field (0.316 Pascal)
Ap
OUTPUT In dB re 1uV
+90
+88
+86
+84
+82
+80
+78
+76
+74
+72
+70
+68
+66
+64
+62
+60
+58
+56
+54
+52
+50
-20
-22
-24
-26
-28
-30
-32
-34
-36
-38
-40
-42
-44
-46
-48
-50
-52
-54
-56
-58
-60
Sensitivity In dB re 1V/Pa
20
50
100
200
500
1k
2k
5k
10k
20k
Frequency (Hz)
ER-11 #2050
Tested By: J.C.V.
Top Curve = Flat Frequency Response
Bottom Curve = DFI Frequency Response

Annex B

Ambient levels

Table B-1

Ambient measurements (dB SPL) obtained using the ATF (right ear*), unoccluded and fitted with the E-A-R 3000 muff, E-A-R Classic foam plug and muff and plug in combination, and Etymotic ER-11 microphone in the diffuse-field equalization mode.

Freq (Hz)	Unoccluded	Muff	Plug	Muff & Plug
12.5	9.1	8.6	8.3	8.4
16	11.6	10.0	10.1	9.4
20	12.9	11.1	10.6	10.6
25	15.0	13.2	11.2	11.3
31.5	22.3	15.2	12.8	11.9
40	15.1	14.3	11.7	11.5
50	39.3	39.4	39.2	39.3
63	54.0	54.0	54.0	54.0
80	27.0	28.4	26.9	26.9
100	14.0	17.8	13.3	13.2
125	18.1	16.5	16.1	16.4
160	10.1	9.3	9.1	9.3
200	10.0	10.0	9.8	10.1
250	10.0	10.6	10.4	10.4
315	17.8	18.1	18.0	17.9
400	10.5	11.2	10.7	10.9
500	14.1	14.0	14.3	14.2
630	6.8	6.7	6.7	6.5
800	8.6	8.1	9.4	8.9
1000	9.5	9.9	9.6	9.7
1250	6.7	6.9	7.0	6.9
1600	6.3	6.4	6.2	6.1
2000	4.3	4.3	4.3	4.2
2500	3.2	4.7	3.7	3.8
3150	2.4	1.8	2.2	2.2
4000	-1.2	-1.4	-1.1	-1.4
5000	-0.8	-0.8	-0.9	-1.0
6300	0.3	0.3	0.1	0.2
8000	1.4	1.4	1.3	1.4
10000	2.6	2.6	2.6	2.6
12500	3.7	3.8	3.8	3.8
16000	4.9	5.0	5.0	5.0
20000	5.6	5.6	5.5	5.6

* Left ear blocked using the E-A-R Classic plug

Table B-2

Ambient measurements (dB SPL) obtained using the ATF (right ear*), unoccluded and fitted with the E-A-R 3000 muff, E-A-R Classic foam plug and muff and plug in combination, and Etymotic ER-11 microphone in the flat frequency mode.

Freq (Hz)	Unoccluded	Muff	Plug	Muff & Plug
12.5	8.3	9.0	8.2	8.3
16	10.8	10.0	9.6	9.4
20	12.1	11.5	10.9	10.2
25	14.4	13.2	11.0	11.3
31.5	22.1	15.2	12.8	11.3
40	14.4	18.8	11.7	11.6
50	39.3	39.5	39.3	39.3
63	54.0	54.0	54.0	54.0
80	26.9	28.4	26.9	26.9
100	14.1	18.1	13.2	13.3
125	18.3	16.1	16.2	16.2
160	10.0	9.6	9.0	9.3
200	9.9	10.4	9.6	10.2
250	10.1	10.6	10.4	10.7
315	17.9	18.0	17.6	18.3
400	10.9	11.7	11.0	10.6
500	14.1	14.2	14.3	14.3
630	7.3	7.1	7.2	7.4
800	8.4	8.9	9.0	9.0
1000	9.9	10.3	10.1	10.0
1250	7.6	7.9	7.5	7.6
1600	7.0	7.5	6.9	7.3
2000	5.5	5.9	6.0	5.8
2500	5.5	6.0	5.3	4.8
3150	4.9	5.0	4.5	4.7
4000	3.8	3.8	3.7	3.8
5000	4.3	4.4	4.2	4.2
6300	5.1	5.1	4.9	4.9
8000	5.6	5.6	5.6	5.6
10000	6.3	6.3	6.3	6.3
12500	7.2	7.2	7.2	7.3
16000	8.2	8.2	8.2	8.3
20000	8.5	8.5	8.5	8.5

* Left ear blocked using the E-A-R Classic plug

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14. ABSTRACT

(U) A study was carried out to assess the validity of using an acoustic test fixture (ATF) to assess the sound reduction afforded by personal hearing protection devices. The ATF under review consists of a head simulator, cast in silicone rubber and covered with artificial skin. Cavities milled out on either side allow for the insertion of snap−in ear modules that incorporate a mechanical reproduction of human aural tissues. The ear canal is terminated by Zwislocki coupler and Etymotic ER−11 measurement microphone and models the impedance of the human ear. The experiment was carried out in a semi−reverberant chamber. On two separate occasions scheduled four months apart, the right ear of the ATF was fitted with an earmuff (E−A−R 3000), an earplug (E−A−R Classic foam plug), and the muff and plug in combination. The non test ear was fitted with the plug. The stimulus was a continuous pink noise, presented free−field at a level of 86 dB SPL using a bank of low, middle and high frequency speakers. Monaural sound level measurements were made under each of these conditions, as well as with the test ear unoccluded. These were replicated three times within session with two different settings of the measurement microphone, diffuse−field equalization and flat frequency response. Measurements were recorded and subsequently subjected to a third octave band analysis from 12.5 Hz to 20 kHz. The results showed that the measurements were highly stable within and across sessions. Differences due to the setting of the measurement microphone were in line with the manufacturer's specifications. When corrected for the effects of bone conduction, occlusion and physiological masking, insertion loss values, the difference between unoccluded and protected levels, closely matched attention data collected from human observers in the range of 500 Hz to 8 kHz.

(U) Une étude a été effectuée afin d'évaluer la validité de l'utilisation d'un « dispositif d'essai acoustique » (acoustic test fixture, ou ATF) destiné à mesurer l'affaiblissement acoustique offert par des dispositifs de protection personnelle de l'ouie. L'ATF à l'étude consiste en un simulateur de tête époxy chargé d'aluminium et recouvert de peau artificielle. Les cavités de chaque côté permettent l'insertion de modules d'oreilles qui reproduisent les mécanismes des tissus auriculaires humains. Le conduit auditif externe, qui aboutissait dans un coupleur de Zwislocki et un micro de mesure Etymotic ER?11, a servi de modèle d'impédance acoustique de l'oreille humaine. L'expérience a eu lieu dans une chambre semi?réverbérante. Au cours de deux expériences distinctes, effectuées à quatre mois d'intervalle, on a successivement placé sur l'oreille droite de l'ATF un cache?oreilles antibruit (E.A.R. 3000), un bouchon d'oreille (bouchon?mousse E.A.R. Classic) et à la fois le cache?oreilles et le bouchon d'oreille. On a posé un bouchon?mousse E.A.R. Classic sur l'oreille non testée. Le stimulus était un bruit rose continu, présenté dans une chambre sourde à 86 dB SPL au moyen d'un ensemble de hauts?parleurs à fréquences basses, moyennes et hautes. Les mesures du niveau sonore monaural ont été effectuées avec chacun des dispositifs, les deux ensemble ainsi qu'avec aucun des deux. On a répété les essais trois fois durant chacune des deux séries d'essais en utilisant deux réglages différents pour le micro de mesure, l'égalisation acoustique en champ diffus et la réponse en fréquence uniforme. Les mesures ont été enregistrées puis soumises à une analyse par bande de tiers d'octave de 12,5 Hz à 20 kHz. Les résultats ont démontré que les mesures étaient très stables durant chacune des séries d'essais ainsi que d'une série à l'autre. Les différences au chapitre de la pression acoustique dues aux réglages du micro de mesure étaient conformes aux spécifications publiées. Ces différences n'ont pas influé sur la perte d'insertion. Après correction pour tenir compte des effets de la conduction osseuse et de l'occlusion et du masquage physiologique, la perte d'insertion (différence selon que le sujet portait ou non les dispositifs de protection de l'ouïe) présentait une corrélation étroite avec l'atténuation acoustique effective au niveau liminaire observé chez des sujets humains dans le plage de 500 Hz à 8 kHz.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) r the contractor"Tasking/Contracting/Sponsor