Health and Safety Executive

# Assessment of subjective and objective measurement systems of earplug attenuation on an individual

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# Assessment of subjective and objective measurement systems of earplug attenuation on an individual

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Standard test methods to determine hearing protector attenuation use a real ear at threshold subjective method, where subjects identify when they can just hear test signals in order to establish their threshold of hearing. The threshold of hearing is measured over a range of test frequencies, with and without a hearing protector worn. The difference in threshold (with and without a hearing protector) provides the attenuation; and a group of results from a range of subjects provides a mean result and a standard deviation in each test frequency band.

Systems that measure earplug attenuation for individual wearers are commercially available and the work detailed in this report aimed to assess the performance and test the reliability of two types of available system: objective measurement and subjective equal loudness. Systems were chosen to represent a type of system rather than a specific model of device and because they: were commercially available through leading manufacturers; were designed for use by operators with a minimal level of training or expertise; could be used with a range of earplugs; and were typical of the state of the art.

Both systems investigated were found to have benefits and limitations. A number of recommendations are presented.

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# EXECUTIVE SUMMARY


## Objectives

BS EN 24869-1 defines a subjective real ear at threshold test for determining the attenuation of hearing protectors. This is a laboratory test reporting the mean and standard deviation of the attenuation obtained on a group of 16 subjects. The standard test data is used to give an estimate of the attenuation of hearing protection when used in the real world. However it is recognised that the likely fit and performance in the real world will be highly variable.

There is a demand for measurements that provide information on the actual attenuation likely to be achieved by individual subjects. Commercial systems are now available but as yet there are no standard specifications for these devices and little information on reliability. Two types of system are currently available, objective systems that perform measurements of sound levels inside and outside the ear of the person wearing the earplug, and subjective systems where the response of the wearer to the level of external sounds with and without the earplug is used to provide an indication of the attenuation.

An objective system and a subjective system were chosen for evaluation. The actual devices were chosen because they are commercially available, require minimal operator training, can be used with a range of earplugs, and each is typical of the state of the art. They were chosen to represent the type of device rather than a specific model.

## Main Findings

The objective system evaluated calculates the equivalent attenuation for a subjective real ear at threshold test, consistent with standards in the USA. It first measures the third octave band frequency spectrum of a broadband random noise sound field from inside and outside the ear of the subject wearing a modified test version of the earplug that incorporates a central measurement probe. The system then applies compensation factors specific for the earplug type obtained from comparative real ear at threshold attenuation measurements.

The subjective system evaluated alternates test tones at each ear of the subject. The subject adjusts the sound level in one ear until the tones are perceived as equally loud in both ears. The process is repeated for test tones at octave intervals between 250Hz and 4kHz. This procedure is performed first with no earplugs, then with an earplug in one ear, and finally with earplugs in both ears. The increase in relative level necessary to restore equal loudness after the earplug is fitted provides a direct measure of the earplug attenuation.

Both systems had benefits and limitations. For an **objective** system these were:

1. Benefit: The system performs precise measurements and requires no input from the subject wearing the earplugs. It is therefore expected to give highly repeatable results for the same earplug and fit. As no response is required from the test subject, it can be used with untrained subjects or those with a hearing impairment.

2. Limitation: The reported results at higher frequencies (4 and 8kHz) appear less reliable.

3. Limitation: Only earplugs supplied by the manufacturer can be tested.

4. Limitation: The probe built into the test earplugs changes the fit of compressible foam earplugs so the attenuation results with the test earplug are not representative of the normal earplug.

5. Limitation: The earplug probe can be blocked causing erroneous attenuation results.

The benefits and limitations of a **subjective** system were:

1. Benefit: The system performs a direct measurement of the attenuation using a subjective assessment. No compensation factors or calculations are required.

2. Benefit: The subjective system can be used with any earplugs.

3. Limitation: Limited precision because of variability in the subject response. Some subjects may be unable to obtain a repeatable result.

The results of this short study were passed for comment to the manufacturers of the systems evaluated. The manufacturer of the objective system responded with detailed comments that are also included in this report.

## Recommendations

Reliance should not be placed on the results of a single test using either a subjective or objective system. The mean and standard deviation for repeat fittings of the earplug should be used.

Systems should alert the operator to results that may indicate a measurement error.

A standard method for computing the attenuation result from the measured parameters is required for objective systems.

# 1 INTRODUCTION

Standard test methods to determine hearing protector attenuation (in both Europe and the USA) use a real ear at threshold subjective method. Subjects identify when they can just hear test signals and this gives their threshold of hearing. The threshold of hearing is measured over a range of test frequencies with and without the hearing protector worn. The difference in threshold with and without the protector gives the attenuation. Results from a group of subjects give a mean result and standard deviation in each test frequency band. This real ear at threshold test can only be performed in extremely quiet laboratory test conditions.

Typical standard deviation values quoted for earplug attenuation in individual frequency bands are generally around 3 to 5dB but can exceed 8dB. It would therefore not be unrealistic to expect the variation in attenuation for individual wearers to exceed 16dB even under laboratory conditions.

Systems that measure earplug attenuation for individual wearers are available. The work reported here assessed the performance of two types of commercially available systems: an objective measurement system, and a subjective equal loudness system.

Objective systems perform precise objective measurements and avoid the variability of subjective evaluations. However the attenuation is not simply the arithmetic difference in the measured attenuated and un-attenuated sound levels. Additional factors are required to calculate the attenuation in each frequency band and for each earplug type. How reliable the final calculated result is, is the question this evaluation has tried to answer.

An alternative subjective system developed for individual testing is loudness balancing. The subject sets the level of tones sounding alternately in each ear to what they perceive as equal loudness. The change in level required when an earplug is inserted in one ear gives an indication of the attenuation added by the earplug. Subjective responses do not yield precise and repeatable results. This evaluation needed to answer the question of how repeatable a result using a loudness balance method could be.

The two systems were chosen for evaluation because they are commercially available through leading manufacturers, are designed for use by operators with a minimal level of training or expertise, can be used with a range of earplugs, and are typical of the state of the art. They were chosen to represent a type rather than a specific model of device. The purpose of the evaluation was to test the reliability of the system type rather than the model. The manufacturers loaned their systems specifically for this evaluation. Both manufacturers were invited to comment on the results of this short evaluation. The manufacturer of the objective system provided detailed comments together with further measurement evidence of their own. These comments are noted in this report.

This report describes the objective and subjective systems evaluated, the results obtained and problems encountered. Comparison is made to the manufacturer's published attenuation data for the earplugs obtained using a standard real ear at threshold test. The Health and Safety Laboratory does not have the facilities to perform real ear at threshold attenuation measurements itself. Additional technical details and results are included in Annex A (objective system) and Annex B (subjective system).

# 2 OBJECTIVE SYSTEM

## 2.1 DESCRIPTION

### 2.1.1 Principle of operation

The system evaluated is designed for use with a range of test earplugs supplied by the manufacturer.

The subject sits in a controlled sound field of broadband random noise wearing a test earplug in one ear. Test earplugs are modified to include an additional central probe running through the earplug that allows measurement of the sound at the earplug tip. Figure 1 shows the test earplugs supplied for this evaluation.

A unit containing two microphones sits beside the ear on the arm of a pair of spectacles. One microphone in the unit connects to the earplug probe to measure the sound level at the earplug tip (the attenuated sound level); the other microphone measures the ambient sound (i.e. the un-attenuated sound level).

The system manufacturer has compared the output from the objective system with the results given by a subjective real ear at threshold test. The results of this comparison have given “compensation factors” for each earplug type. These factors enable the system software to calculate the equivalent real ear at threshold attenuation from the objective measurements.

The system reports the calculated attenuation result at octave intervals from 125Hz to 8kHz, and a single number Personal Attenuation Rating value (PAR) that corresponds to the Noise Reduction Rating or NRR (a single number rating used in the United States). The system does not currently provide the European H, M, L and SNR attenuation values. An uncertainty estimate for the PAR value is given, based on manufacturer’s tests with the specific earplug. Alternatively an individual uncertainty can be calculated from repeat tests.

### 2.1.2 Attenuation measurement equipment and procedure

The objective system evaluated includes:

- a microphone unit with two integral microphones to measure the sound inside and outside the ear,
- a pair of spectacles that support the microphone unit by the ear,
- a loudspeaker that provides the test sound field together with a supporting tripod;
- a selection of earplugs modified with the additional through probe for in ear measurements;
- a software package that controls the test and analysis and the cables for connecting the system hardware to a laptop.

The objective system is software controlled. It can be operated using a normal laptop computer.

The system first performs an initial acoustic check of the hardware operation. The microphone is mounted on the front of the speaker providing a test signal of random noise. If the output from the microphone is within tolerance the test can proceed.

The operator inputs the earplug type so the appropriate “compensation factors” are applied.

The subject sits facing the loudspeaker. Distance markers on the microphone cable show the correct separation between the subject and the loud speaker. The subject fits the modified test earplugs in each ear and wears the spectacles supplied with the system. The microphone unit is fitted to the arm of the spectacles by the ear. A small protruding tube on the microphone unit connects to the earplug probe.

Once the operator starts the test the loudspeaker produces broadband random noise. The system performs an attenuation measurement at one ear without any further input from the operator or subject. The measurement is then repeated on the other ear.

The system reports the attenuation at octave intervals for both the left and right ears.

## 2.2 HSL LABORATORY TESTING

### 2.2.1 Earplugs evaluated

The range of probed earplugs supplied for the evaluation is shown in Figure 1 with the SNR value provided by the manufacturer for the unmodified earplug model. Earplugs O1, O3, and O5 are compressible foam earplugs; O2, O4, and O6 are push-in type earplugs. It should be noted that the manufacturer supplied attenuation data from a recent unpublished test for earplug O1 that gives a higher attenuation than the current published data.

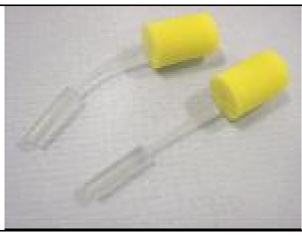
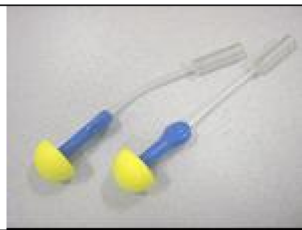
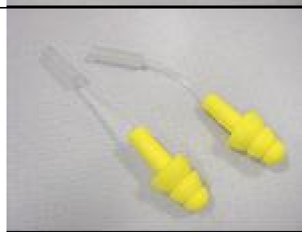
| | | | |
|---|---|---|---|
| Earplug O1 Published SNR 28 Unpublished SNR 33 |  | Earplug O2 SNR 28 |  |
| Earplug O3 SNR 36 |  | Earplug O4 SNR 32 |  |
| Earplug O5 SNR 39 |  | Earplug O6 SNR 38 |  |

**Figure 1 Probed earplugs used for the evaluation of the objective system**

### 2.2.2 Evaluation procedure

The objective system was used in a quiet, but not soundproofed room. The software guided the operator through the test procedure and controlled the progression of the tests. The system was easy to use and there was little opportunity for operator or subject interference.

Measurements were made of earplug attenuation on a group of six subjects, consisting of one inexperienced earplug user (subject 2), three occasional users (subjects 3, 4 and 5), and two trained users of earplugs (subjects 1 and 6). Each subject was tested wearing earplugs in both ears giving 12 result sets for each earplug type.

It was expected the objective system would provide a repeatable result, provided the earplug fit remained consistent. So during tests to evaluate the objective system each subject performed one test with each of the six earplug types supplied, rather than repeat tests with the same earplug.

## 2.3 RESULTS

Results are shown in the following Figures:

- Figure 2 – objective system octave band attenuation results showing the results for the left and right ears of each individual test subject. The results are shown with the mean and standard deviation of the earplug manufacturer's attenuation data.

- Figure 3 – Compensation added by the system to the measured drop in sound level behind the earplug to give the reported octave band attenuation.

- Figure 4 – the mean and standard deviation of the manufacturer's attenuation results. The table below gives mean attenuation values.

- Figure 5 – the mean and standard deviation of the objective system attenuation results. The table below gives mean attenuation values.

Additional tests are described in Annex A.

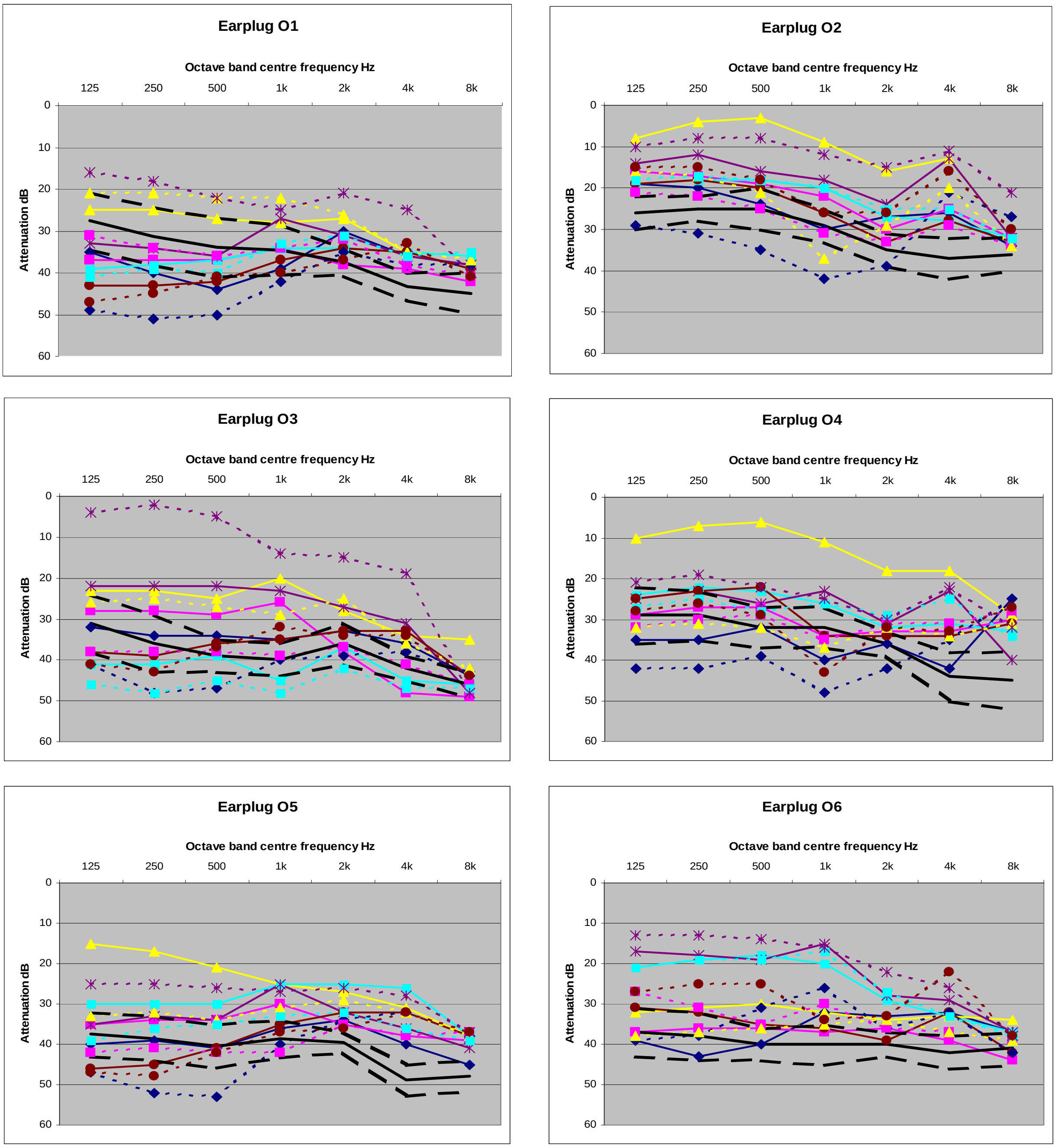
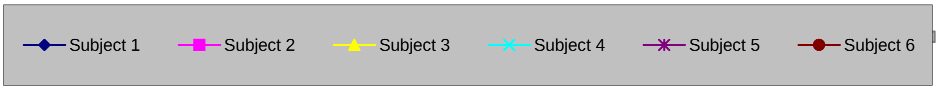
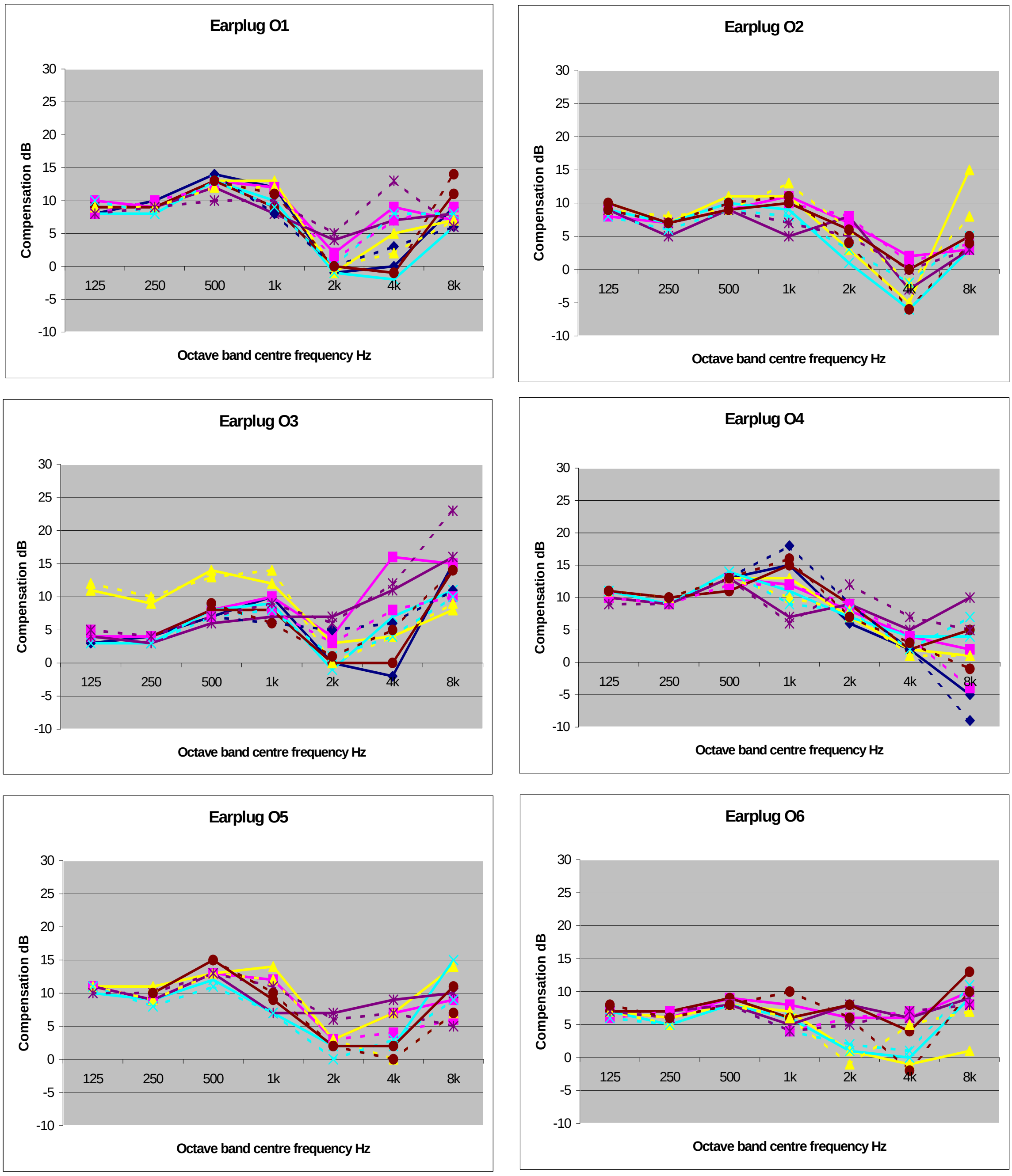



**Figure 2 Octave band attenuation measured with objective system and manufacturer's quoted attenuation**

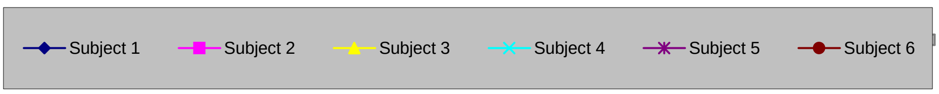
6 subjects as key below; left ear full line, right ear dashed line. Manufacturers attenuation shown in black, mean full line, mean plus and mean minus one standard deviation shown dashed.

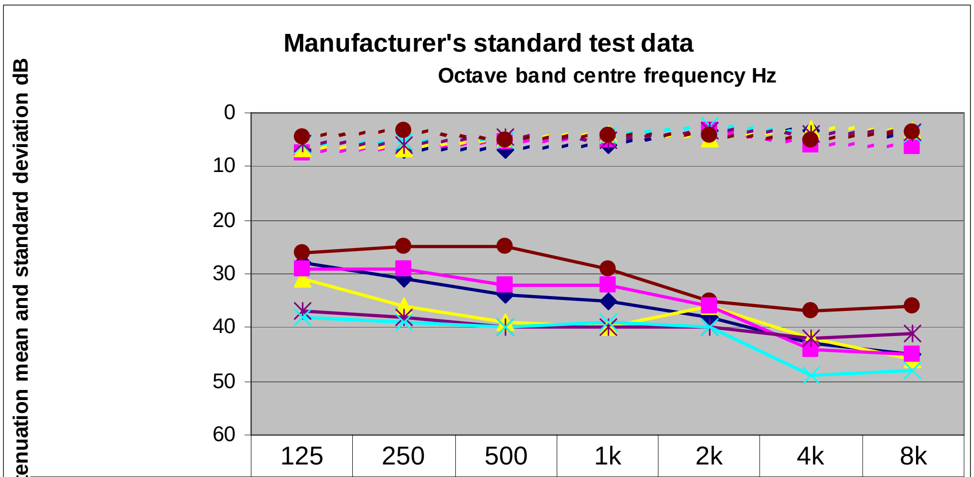





# Figure 3 Compensation added by the system to the drop in sound level behind the earplug to give the reported octave band attenuation

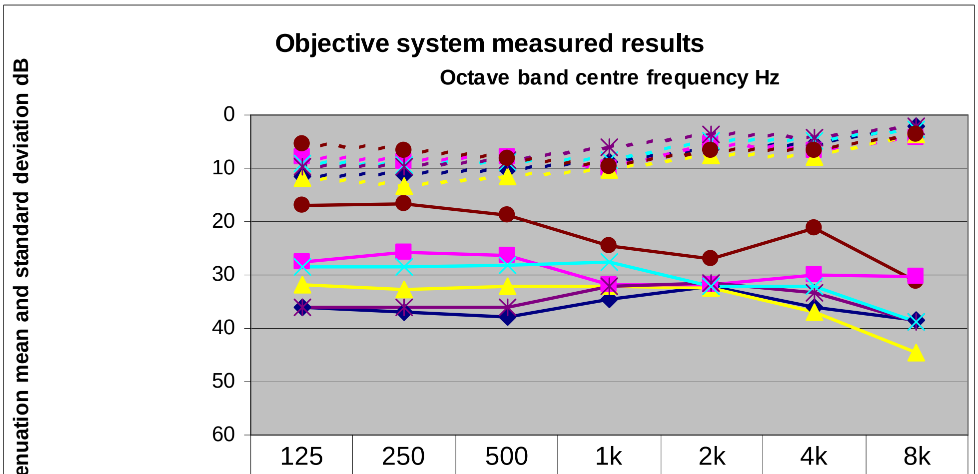
6 subject results shown as key below; left ear full line, right ear dashed line. Where no result is shown the indicated level was below the displayed range.






| | 125 | 250 | 500 | 1k | 2k | 4k | 8k |
|---|---|---|---|---|---|---|---|
| Earplug O1 | 28 | 31 | 34 | 35 | 38 | 43 | 45 |
| Earplug O2 | 26 | 25 | 25 | 29 | 35 | 37 | 36 |
| Earplug O3 | 31 | 36 | 39 | 40 | 36 | 42 | 46 |
| Earplug O4 | 29 | 29 | 32 | 32 | 36 | 44 | 45 |
| Earplug O5 | 37 | 38 | 40 | 40 | 40 | 42 | 41 |
| Earplug O6 | 38 | 39 | 40 | 39 | 40 | 49 | 48 |

**Figures 4 Mean (full line) and standard deviation (dotted line) of earplug attenuation; manufacturer's BS EN 24869:1 standard test data**




| | 125 | 250 | 500 | 1k | 2k | 4k | 8k |
|---|---|---|---|---|---|---|---|
| Earplug O1 | 36 | 37 | 38 | 35 | 32 | 36 | 38 |
| Earplug O2 | 17 | 17 | 19 | 24 | 27 | 21 | 31 |
| Earplug O3 | 32 | 33 | 32 | 32 | 32 | 37 | 45 |
| Earplug O4 | 28 | 26 | 26 | 32 | 32 | 30 | 30 |
| Earplug O5 | 36 | 36 | 36 | 32 | 31 | 33 | 39 |
| Earplug O6 | 29 | 29 | 28 | 28 | 32 | 32 | 39 |

**Figure 5 Mean (full line) and standard deviation (dotted line) of earplug attenuation; objective system results**

## 2.4 DISCUSSION OF RESULTS

### 2.4.1 Ease of use

The system evaluated proved to be simple to set up, and was used successfully in a normal quiet room. It required no response from the subject so no subject training was required. It could potentially be used with subjects with a hearing impairment.

### 2.4.2 Do the results compare to the manufacturer's attenuation data?

The Health and Safety Laboratory does not have the capacity to perform real ear at threshold attenuation measurements. In this evaluation only the manufacturer's published data is available for comparison with the system results.

Figures 4 and 5 show the objective system results for the push-in type earplugs O2, O4 and O6 are comparable with the manufacturer's data; both report the lowest to highest attenuation order as O2, O4, O6. The objective system reports lower mean attenuation results than the manufacturer's data and generally a wider standard deviation, which is consistent with the expected real world performance.

The compressible foam earplugs have each given a higher mean attenuation result than the push-in type earplugs when tested with the objective system. Earplugs O3 and O5 give mean results close to the manufacturer's value, but with a higher standard deviation while earplug O1 has given a significantly higher mean attenuation than the manufacturer reports at the lower frequencies.

The results confirm the objective system has provided results that are comparable with expected real world performance for push-in type earplugs. However the results for compressible foam earplugs are higher than expected and suggest the modified test earplugs have perform differently to the normal earplugs they represent.

**SUMMARY**

- The objective system has provided realistic results for the three push-in, premoulded type earplugs tested. The compressible foam earplugs provided higher attenuation than expected when tested with the objective system.

### 2.4.3 Does the probe alter the fit of compressible foam earplugs?

Four of the six test subjects thought the probe provided a more rigid core to the compressible foam earplugs, making it easier to obtain a deep fit. The push-in, premoulded earplugs already have a rigid core, and the probe was not reported to change the fit.

The manufacturer of the objective system commented that the probe tube is very thin and soft and they would advise subjects to be instructed not to use the probe to aid insertion.

**SUMMARY**

- The probe may aid the insertion of the test compressible foam earplugs so the fit is not comparable to that of the normal earplug they represent.

### 2.4.4 Can the earplug probe be blocked inside the ear?

Subject 4 had an accumulation of wax in their ears. This visibly coated the first earplug tested (earplug O3). Exceptionally high attenuation was measured by the objective system (Figure 2). It is probable this result was caused by earwax blocking the probe opening.

Tests, reported in Annex A, confirmed blockage of the probe tube was also possible with a deep fit. Blockage was characterised by exceptionally high attenuation at 500Hz and below. The right ear attenuation results for Subject 1 wearing foam earplugs O1, O3, and O5 (Figure 2) are possibly indicative of probe blockage.

The manufacturer of the objective system commented that if a subject achieved a PAR value of more than 42dB they would recommend that the test be repeated, as the result was likely to be an error. However, the system's compensation to simulate bone conduction effects is likely to keep PAR values below 42dB (see section 2.4.5) and an automatic system warning would be more effective.

The manufacturer said they would recommend the test operator pulled a deeply fitted earplug slightly out of the ear canal to avoid a blockage.

**SUMMARY**

- The earplug probe can become blocked with earwax and by being pushed deep into the ear canal. Blockage will result in erroneous high attenuation results, at low frequencies.
- An objective system should warn the operator if the results suggest the probe is blocked.
- The manufacturer recommends pulling a deeply fitted earplug out slightly before testing to avoid a blockage.

### 2.4.5 Compensation factors applied to calculate the attenuation

The reliability of the compensation factors used to convert the third octave band sound levels measured inside and outside the ear to the equivalent subjective test result is crucial to the objective system performance.

The difference between the reported octave band attenuation and the uncorrected drop in level across the earplug gives the apparent compensation added by the system software. This compensation is plotted in Figure 3.

Below 1kHz there is little spread in the compensation applied to the results for each subject. The exception are anomalous left and right ear results for subject 3 and earplug O3 that suggest the operator had input the wrong earplug type at the start of the test.

The manufacturer confirmed the system limits the maximum attenuation reported at and above 2kHz. This is to simulate actual limiting of the protector attenuation caused by a low level of un-attenuated sound reaching the ear by bone conduction. The compensation applied at and above 2kHz is varied to provide this simulated limiting.

This limiting has had the disconcerting effect of causing a discontinuity between the limited results at 2kHz and above, and the unlimited results below 2kHz (Figure 2) that cannot be representative of the actual earplug performance. This transition in reality must be more gradual.

There is also a concern that compensation at the higher frequencies might mask a clearly random or erroneous result and present it as a realistic attenuation result. The range of compensation applied to the 4kHz and 8kHz bands has varied by up to 20dB for the same earplug but different subject results. The manufacturer confirmed the 8kHz results to be unreliable and the wide spread in compensation applied at 4kHz suggests the compensation may simply mask measurement errors.

Figure 2 reports all subjects had a significant attenuation dip at 4kHz with earplug O2. Figure 3 confirms this coincides with a significant change in the compensation applied. The 4kHz dip is not characteristic of the earplug manufacturer's attenuation data (Figure 4) and this result is possibly erroneous.

The manufacturer commented that low attenuation at 4kHz is uncommon but not unknown.

The contribution of the compensation factors to the attenuation result is clearly significant, and reliability must be assured. As yet there is no standard for how the factors are obtained and the calculations made. Without a standard method for this crucial part of an objective system, reliability of individual systems cannot be confirmed.

**SUMMARY**

- An objective system applies compensation, according to the earplug type, to the measured results to provide the attenuation. An incorrect result will be provided if the operator enters the wrong earplug type.
- At and above 2kHz the attenuation reported is limited to compensate for bone conduction. When high attenuation is also reported at low frequencies this creates a discontinuity in the reported attenuation between 1 and 2kHz. Bone conduction corrections need to be applied more gradually from lower frequencies.
- Limiting of the reported attenuation above 1kHz gave variations of 20dB in the compensation applied to the results for different subjects. This manipulation of the data while justified, has the potential to mask erroneous results.
- The system manufacturer confirmed the 8kHz attenuation results are unreliable. The wide spread in applied compensation at 4kHz suggests compensation factors may be masking errors at this frequency too.
- Without a standard method for determining compensation factors individual objective systems cannot be validated.

## 2.5 CONCLUSIONS ON THE OBJECTIVE SYSTEM

The objective system evaluated was simple to operate and was successfully used in a normal quiet room. As it required no subject response, it is suitable for a wide range of subjects, including untrained or hearing-impaired subjects who might find difficulties with a subjective system. The system evaluated performs sound measurements inside and outside the ear of a subject wearing earplugs modified with a through probe. The probe allows measurements of the sound at the inside tip of the earplug. Compensation factors, specific for the earplug, convert the drop in level measured across the earplug to the attenuation.

The system provides results from a single run, and will also provide the mean and standard deviation from repeat measurement runs with the same subject and earplug.

The system evaluated had been through detailed development however limitations with the objective system were apparent.

1. The probe in the test earplugs provided a core to compressible foam earplugs that made deep fitting easier. This improved fit was confirmed by attenuation results that were significantly higher than expected at low frequencies.

2. The opening of the earplug probe can be blocked by wax or by the earplug being pushed deep into the ear canal and against the ear canal wall. Blockage resulted in high and erroneous attenuation results.

3. Sound reaching the ear by bone conduction and bypassing the ear canal limits the attenuation of any hearing protector. The objective system evaluated limited the attenuation reported at and above 2kHz to simulate bone conduction. This created a discontinuity where the lower frequency unlimited results met the limited high frequency results. This discontinuity is clearly not realistic and perhaps limiting at lower frequencies may be appropriate.

4. Limiting of the reported attenuation gave variations of 20dB in the compensation applied to the measured data for different subjects. This manipulation of the data while justified, has the potential to mask errors. A warning of possible measurement errors is required.

5. The system reliability appears to decrease at higher frequencies. The manufacturer confirmed the 8kHz attenuation results are unreliable and not used in the calculation of the PAR value. The results at 4kHz also suggested poor reliability. The wide spread in applied compensation allowed to simulate limiting will mask excessive results, while a consistent minimum attenuation reported for one earplug at 4kHz was incompatible with the manufacturer's attenuation data.

6. The contribution of the compensation factors to the attenuation result is significant but as yet there is no standard for how the factors are obtained and used in any calculation. Without a standard method the reliability of individual objective systems cannot be confirmed. Until a standard is available users should look to the manufacturer or supplier to ensure system results have been confirmed as comparable to those from a standard subjective method.

# 3 SUBJECTIVE SYSTEM

## 3.1 DESCRIPTION

### 3.1.1 Principle of operation

Subjective systems rely on the subject's perception of the sound level to determine the change in level in the ear when an earplug is fitted. The system evaluated uses a novel loudness balance method where the subject sets the sound in one ear to match the loudness of the sound heard in the other ear. Subjective tests can provide a direct measure of the attenuation with no requirement for post measurement correction. However the precision of a subjective response is variable and some subjects may not be able to provide reliable or repeatable results.

A subjective system has the advantage that any earplug can be tested as no modification or compensation factors are required.

The subjective system evaluated is a simple system that presents pulsed tones alternately to each ear through large volume audiometric style headphones. Tones are presented at octave intervals between 250Hz and 4kHz. If a subject has difficulties performing the loudness balance over the full frequency range a single check at 500Hz can be performed instead.

At each frequency the subject is asked to raise or lower the level in one ear until it matches the perceived level in the other ear. This procedure is repeated with the addition of an earplug in one ear, and then in both ears. The change in the sound level required to restore equal loudness after an earplug has been fitted gives the earplug attenuation at each test frequency.

The system evaluated provides the octave band attenuation results from 250Hz to 4kHz. This frequency range is not sufficient to make a calculation of the protector H, M, L and SNR values.

### 3.1.2 Measurement procedure

The system is supplied with large volume audiometric style headphones, and software that controls the test procedure and the tones presented at each ear.

The operator initially records the earplug type and published NRR (noise reduction rating) value before the test starts.

A pre-test check is performed at 500Hz to ensure the subject can obtain a repeatable result. The subject is not required to have the same hearing acuity in both ears, but does need the ability to set the levels perceived as equally loud with a degree of repeatability. The subject can proceed if they make two consecutive loudness balances within 5dB of each other.

The first test stage is performed without earplugs. The subject adjusts the sound level of the tones in one ear to the loudness of the same tones in the other ear. This is repeated at each test frequency.

At the second test stage an earplug is fitted to the right ear, and the subject repeats the operation of equalising the loudness in each ear starting at 500Hz. If the attenuation at 500Hz is considered too low the operator is warned the earplug is poorly fitted and this stage can be repeated after refitting.

At the third test stage an earplug is fitted in the left ear (both ears now with earplugs) and the subject again repeats equalisation of the loudness in each ear at each test frequency. This final measurement sequence provides the attenuation of the earplug in the left ear.

The subjective system reports the attenuation at the test octave intervals and a PAR (Personal Attenuation Rating) value for each ear. As with the objective system this PAR value is said to equate to the Noise Reduction Rating (NRR) value used in the United States.

## 3.2 HSL LABORATORY TESTING

This section reports measurements of earplug attenuation with the subjective system on a group of six subjects. Some additional tests of system accuracy are reported in Annex B.

### 3.2.1 Earplugs evaluated

A variety of earplugs from different manufacturers was used in this evaluation and is shown with the manufacturer's quoted SNR value in Figure 6. It should be noted that earplugs S1 and O1 are the same earplug type, earplug O1 being the modified version with the added probe.

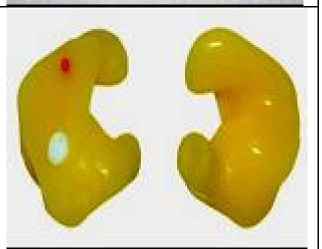
| | | | |
|---|---|---|---|
| Earplug S1<br>SNR 28 |  | Earplug S2<br>SNR 30 |  |
| Earplug S3<br>SNR 35 |  | Earplug S4<br>SNR 27 |  |
| Earplug S5<br>SNR 28 |  | Earplug S6<br>(custom moulded)<br>SNR 29 |  |

**Figure 6 Earplugs used for the evaluation of the subjective system**

### 3.2.2 Evaluation procedure

This subjective system relies on individuals being able to perform a repeatable loudness balance. Given that subject repeatability is the crucial weakness of a subjective system each earplug type was tested repeatedly with the same subject.

The six subjects, one inexperienced earplug user (subject 2), three occasional users (subjects 3, 5 and 7), and two trained users of earplugs (subjects 1 and 6) performed up to 5 repeat tests, with testing discontinued when the subject considered their concentration was lapsing.

Testing was performed in a quiet, but not sound proofed, room. The software guided the user and test subject through the test.

### 3.3 RESULTS

The system proved easy for the operator to use but the subject required a degree of skill and concentration to perform the loudness balance.

Figure 7 shows the subjective system results. Each individual graph shows the results of repeated measurement runs with one subject and one earplug type. The earplugs were refitted between each test run so the results include a degree of variation due to changes in the fit as well as variability in the system results. The manufacturer’s published attenuation data is shown with these results for comparison.

Figure 8 shows the corresponding averaged results with the standard deviation. Again the mean and the standard deviation from the manufacturer’s published data are shown for comparison.

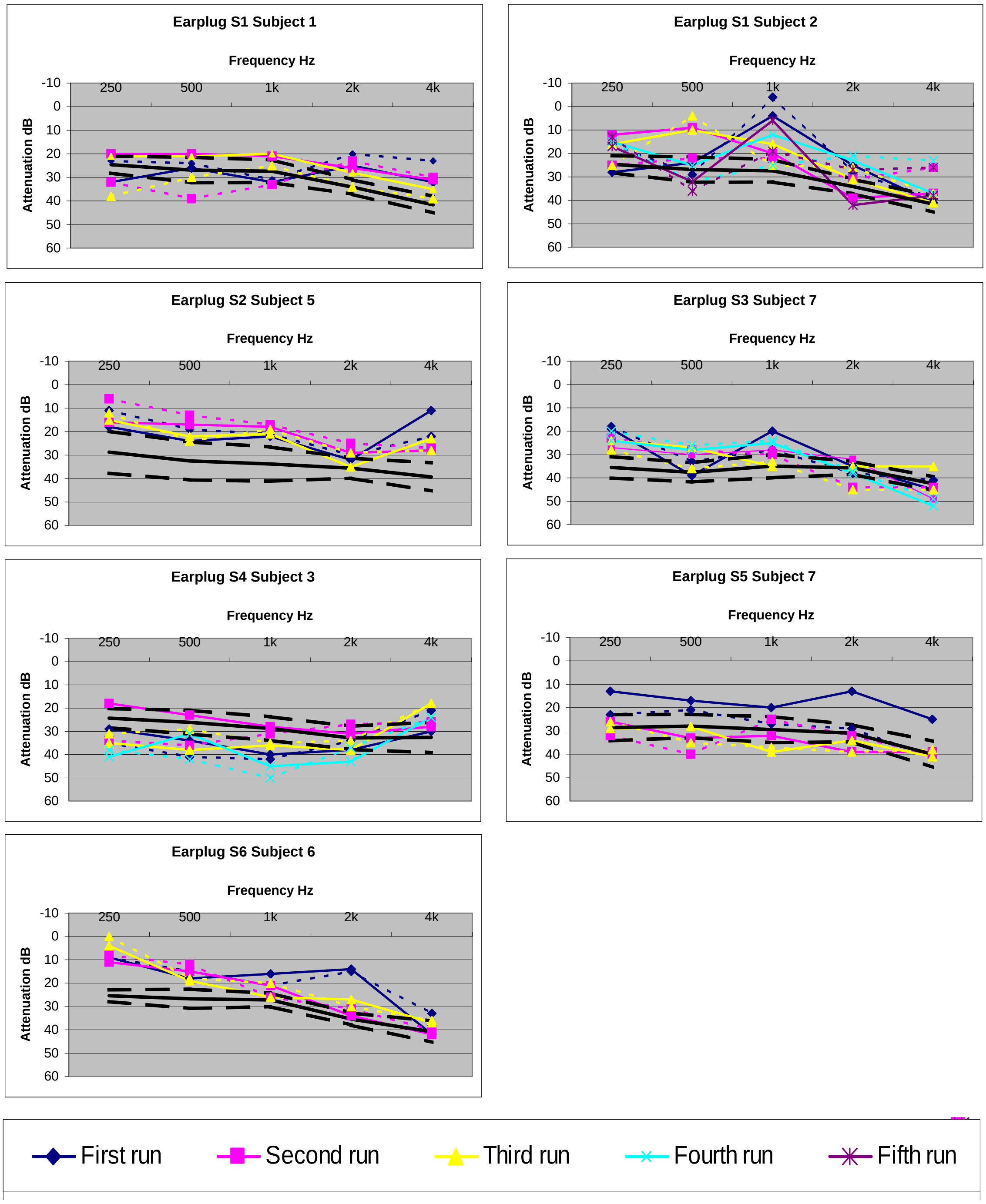



**Figure 7 Subjective system attenuation results with manufacturer's data**

Repeat tests shown in individual colours, left ear full line, right ear dashed line. Manufacturer's attenuation data shown in black, mean full line, mean plus and mean minus one standard deviation shown dashed.

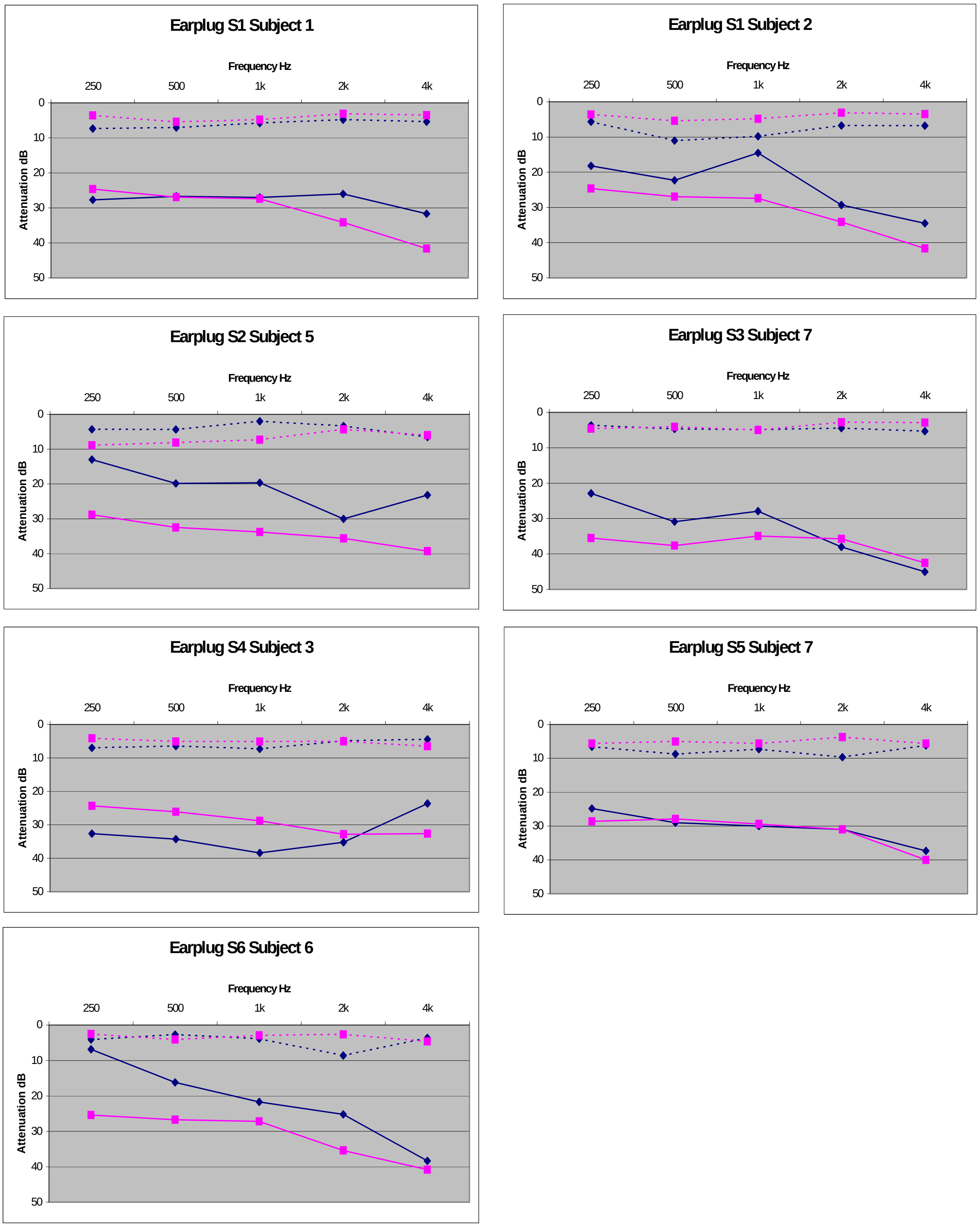



**Figure 8 Mean and standard deviation of subjective system attenuation with manufacturer's data**

Subjective system results shown in dark blue, manufacturer's attenuation data in pink. Mean attenuation shown in a full line, standard deviation shown dashed.

## 3.4 DISCUSSION OF RESULTS

### 3.4.1 Repeatability of test results

Subjects needed a degree of skill and concentration to perform the loudness balance operation. No subject, taking part in this evaluation, considered they were unable to perform the loudness balance although the oldest subject (subject 1 aged 56) reported that some tones were perceived as having a different sound quality in each ear and this made loudness balancing more difficult. Variations in subject skill are seen in the repeatability of the results each subject obtained. Figure 7 shows subject 2 has demonstrated poor repeatability with wide variations in attenuation both between test runs and adjacent test frequencies. Subject 5 with earplug S2 (Figure 8) did best with a lower standard deviation at all frequencies than the manufacturer's attenuation data. The results for the other four subjects show a standard deviation typically between 2 and 10dB.

It is clear that the subjective system and its loudness balance method is relatively imprecise. To ensure sufficient reliability tests must be repeated, and the mean and standard deviation of repeat measurements taken into account when predicting the attenuation the subject achieves. A system also needs a means of rejecting or warning the operator of results that show extremely poor repeatability.

**SUMMARY**

The subjective system is relatively imprecise. Single measurements will not be reliable and the mean and standard deviation from repeat tests should be used to predict the real world attenuation for the subject.

Systems need a means of identifying results with extremely poor repeatability that will not be reliable.

### 3.4.2 Comparability with expected real world performance

The attenuation achieved in the real world is expected to be similar to or less than the manufacturer's reported mean. The results show subjects generally achieved the expected real world performance with only Subject 3 using earplug S4 achieving attenuation higher than the manufacturer's reported mean at most frequencies.

**SUMMARY**

Attenuation results appear comparable to the expected real world performance of the earplugs.

### 3.4.3 Features making equal loudness balancing difficult

Some of the features of the subjective system evaluated made loudness balancing more difficult.

The system provided a visual display of the changes in level made by the subject. A subject may look for visual clues from this display instead of performing the loudness balance.

The subject must select a higher or lower level range if they cannot obtain equal loudness within the displayed range. One subject carried out a test (not included in the results) only using the displayed range, as they failed to understand this facility.

**SUMMARY**

The method the subject uses to adjust the sound level should be made as simple as possible. Any peripheral indicators of the level that may confuse the subject should be avoided.

### 3.4.4 De-rating of results

It was noted that while the subjective system provides the actual attenuation measured at octave intervals it de-rates the reported PAR value by 5dB. It is unclear why this de-rating is applied, and what benefit is intended. A de-rating based on the standard deviation obtained from repeat runs would be more appropriate.

**SUMMARY**

Results should not be de-rated by a fixed value. De-rating must be based on the standard deviation of repeat measurement runs.

### 3.4.5 User operation check

The system evaluated has no user calibration check. A user check to confirm correct operation within specific tolerances should be required.

## 3.5 CONCLUSIONS ON THE SUBJECTIVE SYSTEM

The subjective system evaluated was simple to operate, being software controlled. It required no special facilities and could be used in a normal quiet room. No special modifications to the earplug or post measurements corrections were required. The loudness balance method used by the system gave results that appeared comparable to the expected real world performance.

1. A subjective system will require the test subject to have a degree of concentration and skill to perform the test. The precision of the result will vary from subject to subject.

2. Older subjects, and those with a hearing impairment may have increased difficulty using a subjective system.

3. Where the subject can perform the loudness balance operation the standard deviation will generally be between 2 and 10dB for repeat measurements with the same earplug and subject, and typically higher than the standard deviation given with the manufacturer’s data for a group of subjects.

4. A loudness balance system is not sufficiently repeatable for single measurements to be reliable; instead the mean and standard deviation from repeat runs should be obtained for the subject and earplug.

5. One subject out of the six taking part in this evaluation provided results with no apparent degree of repeatability. Systems should give a warning to the operator if results are indicative of severe subject error.

6. Features that distract the operator, such as visual level displays, and overly complex systems for changing the level during the loudness balance operation should be avoided. Simple controls with no distracting indicators should be preferred.

7. The subjective system evaluated de-rated the PAR value reported by a fixed value. De-rating should ideally be based on the standard deviation obtained from repeated measurements not a fixed value.

8. The system evaluated did not include a user calibration check. Systems should include some user check.

# 4 OVERALL CONCLUSIONS

1. Systems that provide an indication of protector attenuation for an individual have the potential to assist with training on fitting the protector correctly, and the correct selection of hearing protection on an individual basis.

2. Both the objective and subjective systems were software controlled and simple to operate. Both systems could be used in a normal quiet room.

3. Both systems provided results from a single measurement run while the objective system also allowed the mean and standard deviation from repeat runs to be reported.

4. Objective systems require no subject response, instead the sound level inside and outside the ear is measured and this provides an indication of the earplug attenuation. This allows an objective system to be used with any subject, even those with a significant hearing impairment.

5. An objective system uses a probe through the earplug to measure the sound level inside the ear. This can be blocked by both earwax and by deep fitting within the ear canal. Excessive and erroneous attenuation results will be given if the probe is blocked.

6. The probe through the earplug can change the fit and the attenuation result of compressible foam earplugs that have no rigid core. The results obtained for earplugs with an existing rigid core are unlikely to be effected by the probe.

7. An objective system should warn the operator of high attenuation results that may indicate a measurement error. This warning will need to be triggered before any limiting of the results that may be applied to simulate bone conduction.

8. An objective system performs calculations to convert the sound level drop across the earplug to the attenuation. Individual factors are used in the calculation for each earplug type and each frequency band. The contribution of these factors to the attenuation result is significant but as yet there is no standard for how the factors are obtained and used. The system evaluated had performed comparative measurements using a standard subjective test method. Users will need to confirm that the factors used in the calculations of the attenuation have been obtained from a reliable comparison with a standard test method.

9. The precision of the attenuation reported with an objective system appears to decrease at higher frequencies. The manufacturer of the system evaluated confirmed the 8kHz results were unreliable, and were not used in the PAR (Personal Attenuation Rating) calculation. This evaluation considered the 4kHz results were less reliable too. There should be a warning if a possible anomalous result dominates the reported PAR value. It should be noted that a low attenuation result would dominate the overall rating, not a high attenuation.

10. Subjective systems rely on the response of the subject to the loudness of test sounds to determine the attenuation of the earplug, and this makes them relatively imprecise. The precision of the result will vary from subject to subject.

11. The subjective system evaluated gave results for repeat tests with the same subject and earplug that had a standard deviation between 2 and 10dB. Clearly a subjective system is not sufficiently precise for single measurements to be reliable or representative; instead the mean and standard deviation from repeat runs should be obtained and used to provide the attenuation result.

12. Some subjects (particularly those with a hearing impairment) may be unable to provide a reliable and repeatable response with a subjective system.  Systems should warn the operator if results are indicative of severe subject error.

13. With a subjective system features that distract the operator such as a visual display or over complex subject actions or controls should be avoided as they lead to increased errors. Simple controls with no distracting indicators should be preferred.

# 5 RECOMMENDATIONS

Each system is shown to have benefits and limitations as one would expect, with the following recommendations being made:-

- Reliance should not be placed on the results of a single test using either a subjective or objective system
- The mean and standard deviation for repeat fittings of the earplug should be obtained.
- Systems should alert the operator to results that may indicate a measurement error.
- A validated standard method for computing the attenuation result from the measured parameters is required for objective systems

The results of the study have been forwarded to the respective manufacturers of the two systems evaluated.

# 6 REFERENCES

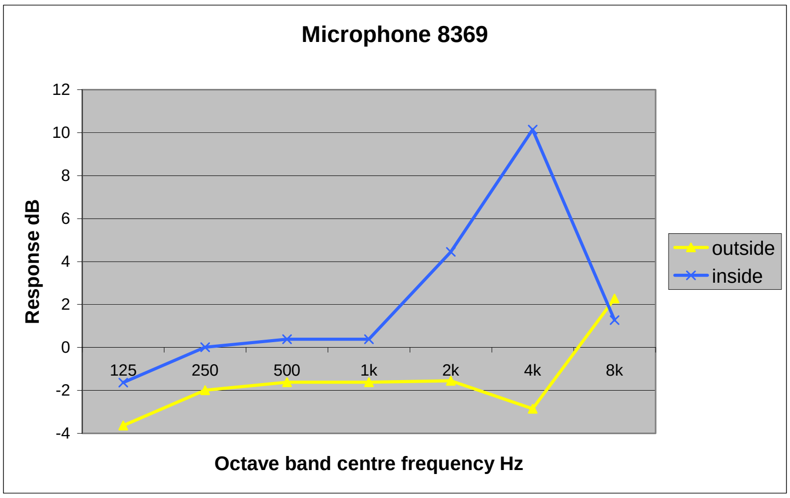
BS EN 24869-1:1993
Acoustics – Hearing protectors – Part 1: Subjective method for the measurement of sound attenuation

# ANNEX A ADDITIONAL OBJECTIVE SYSTEM TEST RESULTS

## A.1 OBJECTIVE SYSTEM MICROPHONE FREQUENCY RESPONSE

The system manufacturer supplied two identical dual element microphone units (identified as microphone numbers 8369 and 8417). Each unit comprised two microphones, for measuring the outside sound level and the in-ear sound level. The frequency response of these microphones was tested under free-field conditions, in a field of random noise; the microphones were positioned perpendicular to the direction of sound. The response was obtained by comparison with a reference Brüel & Kjær 4190 free field response microphone positioned so that it faced the direction of sound.

The frequency response of the two units is shown in Figure A1. Results are given for the outside sound level and in-ear sound level elements. Each unit shows a similar response. The inside elements show a resonance between 2 and 4kHz. The manufacturer confirmed the earplug compensation factors will correct the frequency response of the microphones. However it is clear this correction will be more complex at and above 2kHz and potentially a source of uncertainty in the measured attenuation.



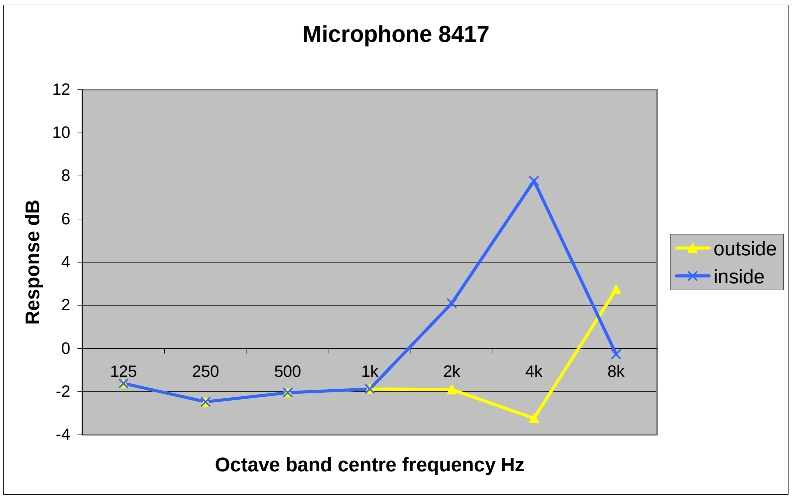




**Figure A1 Frequency response of two microphone units supplied with the objective system. Measurement performed in free field conditions perpendicular to the direction of sound.**

## A.2 TESTING FOR PROBE TUBE OBSTRUCTION IN THE EAR

The objective system sometimes indicated extremely high attenuation at low frequencies. It was apparent in one case this was due to earwax entering the probe tube. In others, it was suspected that the probe opening was blocked by being pushed against the ear canal wall.

### A.2.1 Using a replica ear

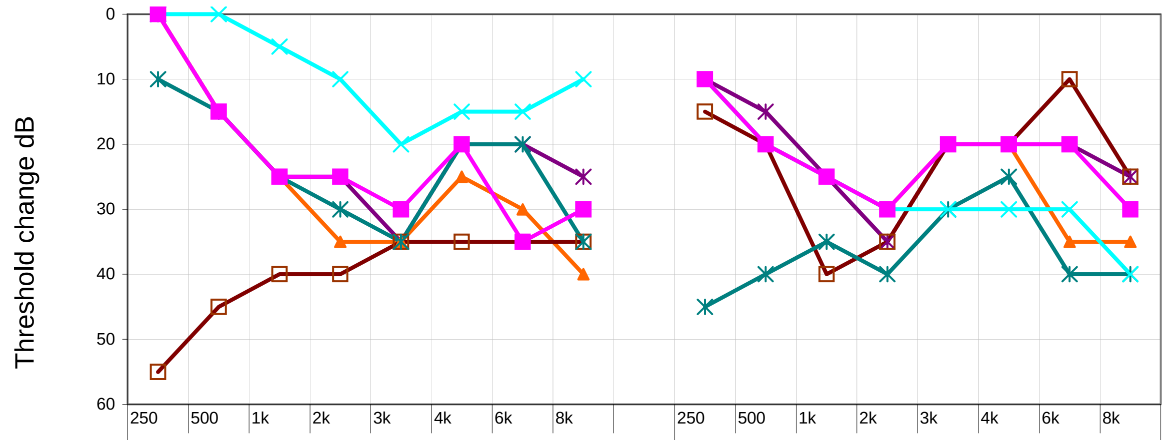
Earplugs supplied with the objective system were fitted in the ear canal of a replica ear, moulded in a clear pliable resin. The outer end of the earplug probe tube, that would normally connect to the microphone, was sealed inside the coupler of a sound calibrator. The calibrator supplied a constant 250Hz tone through the probe into the ear canal of the replica ear. A second probe was inserted through the wall of the replica ear to allow measurement of the relative sound level in the ear canal.

The measured sound level in the ear canal was generally constant within 1.5dB for each earplug type, provided the earplug effectively sealed the canal and the probe opening in the ear was unobstructed. However the sound level dropped by 30dB if the probe opening was pushed against the ear canal wall blocking the end of the probe tube. Pulling the earplug back to release the obstruction restored the sound in the ear canal to the unobstructed level.

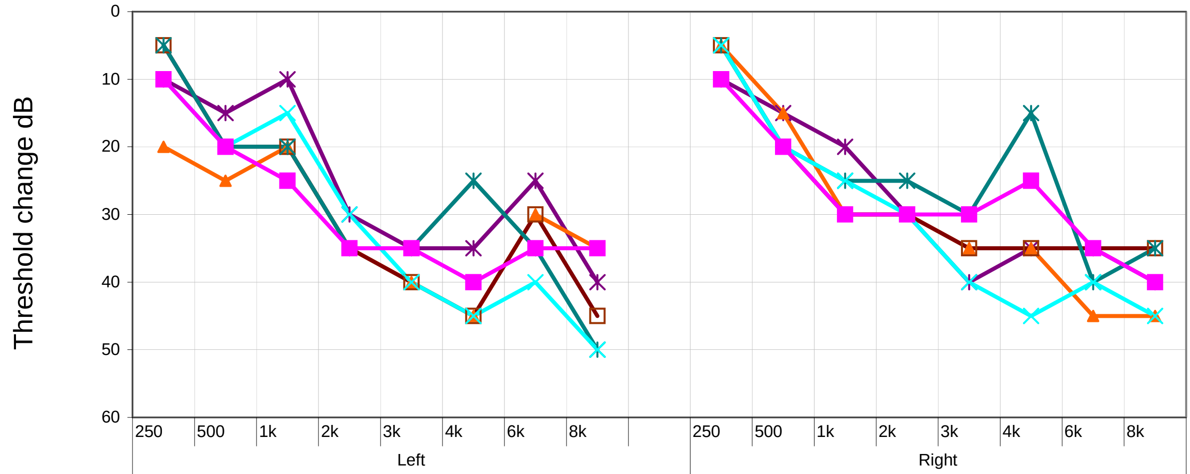
### A.2.2 Using human subjects and audiometric testing

The test described in A.2.1 confirmed the probe could be blocked if the earplug tip was pushed against the ear canal wall of a replica ear. To confirm whether such an obstruction could occur in real ears, four subjects (three subjects from the original group used for the attenuation measurements and subject 7 from the subjective system evaluation) took part in audiometric tests of the earplug attenuation. Measurements were made of their hearing threshold with and without the earplugs. The earplug probe tube was left open at the end opening outside the ear canal and shortened to avoid contact with either the subject's pinna or the audiometer headphone. Figures A2a and A2b show the change in the threshold of hearing with and without the earplug. The tables of data included in these figures show the results for each subject and earplug tested.

The upper chart in Figure A2a (subject 1) shows abnormally high changes in hearing threshold with earplugs O3 (left ear) and O4 (right ear) at low frequencies, confirming a loss of transmission through the probe, which indicates a blockage. It was noted that some abnormally high attenuation results at low frequencies were obtained for this subject when the system was evaluated, which could have been caused by a similar probe blockage.

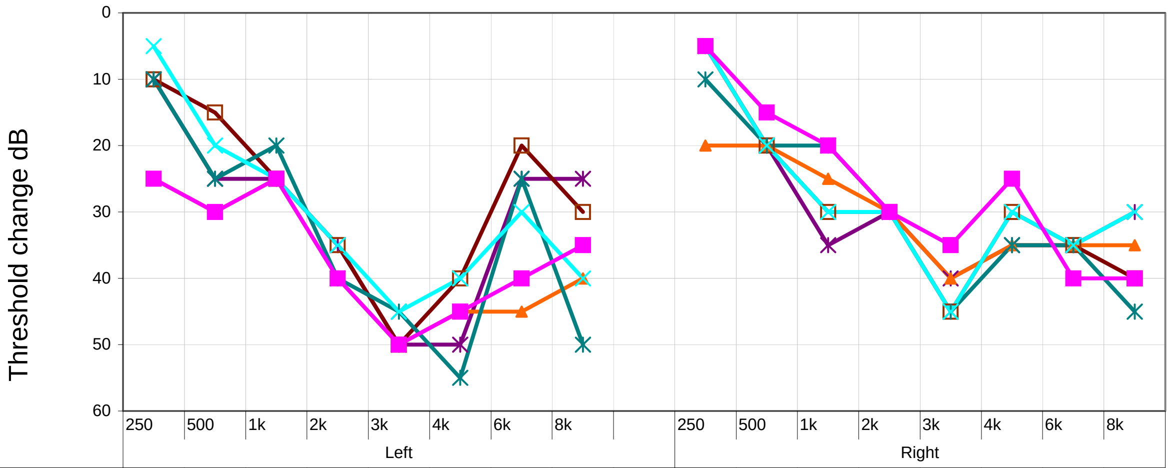



| | Left | | | | | | | | | Right | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 250 | 500 | 1k | 2k | 3k | 4k | 6k | 8k | | 250 | 500 | 1k | 2k | 3k | 4k | 6k | 8k |
| Subject 1 O1 | 0 | 15 | 25 | 25 | 35 | 20 | 20 | 25 | | 10 | 15 | 25 | 35 | 20 | 20 | 20 | 25 |
| Subject 1 O2 | 0 | 15 | 25 | 35 | 35 | 25 | 30 | 40 | | 10 | 20 | 25 | 30 | 20 | 20 | 35 | 35 |
| Subject 1 O3 | 55 | 45 | 40 | 40 | 35 | 35 | 35 | 35 | | 15 | 20 | 40 | 35 | 20 | 20 | 10 | 25 |
| Subject 1 O4 | 10 | 15 | 25 | 30 | 35 | 20 | 20 | 35 | | 45 | 40 | 35 | 40 | 30 | 25 | 40 | 40 |
| Subject 1 O5 | 0 | 0 | 5 | 10 | 20 | 15 | 15 | 10 | | 10 | 20 | 25 | 30 | 30 | 30 | 30 | 40 |
| Subject 1 O6 | 0 | 15 | 25 | 25 | 30 | 20 | 35 | 30 | | 10 | 20 | 25 | 30 | 20 | 20 | 20 | 30 |

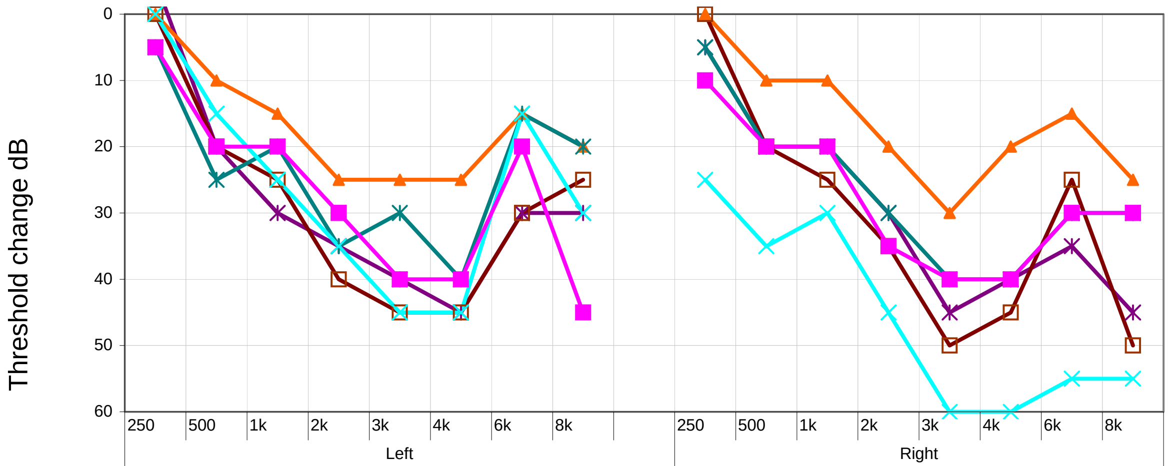



| | Left | | | | | | | | | Right | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 250 | 500 | 1k | 2k | 3k | 4k | 6k | 8k | | 250 | 500 | 1k | 2k | 3k | 4k | 6k | 8k |
| Subject 3 O1 | 10 | 15 | 10 | 30 | 35 | 35 | 25 | 40 | | 10 | 15 | 20 | 30 | 40 | 35 | 35 | 40 |
| Subject 3 O2 | 20 | 25 | 20 | 35 | 40 | 45 | 30 | 35 | | 5 | 15 | 30 | 30 | 35 | 35 | 45 | 45 |
| Subject 3 O3 | 5 | 20 | 20 | 35 | 40 | 45 | 30 | 45 | | 5 | 20 | 30 | 30 | 35 | 35 | 35 | 35 |
| Subject 3 O4 | 5 | 20 | 20 | 35 | 35 | 25 | 35 | 50 | | 5 | 20 | 25 | 25 | 30 | 15 | 40 | 35 |
| Subject 3 O5 | 10 | 20 | 15 | 30 | 40 | 45 | 40 | 50 | | 5 | 20 | 25 | 30 | 40 | 45 | 40 | 45 |
| Subject 3 O6 | 10 | 20 | 25 | 35 | 35 | 40 | 35 | 35 | | 10 | 20 | 30 | 30 | 30 | 25 | 35 | 40 |

**Figure A2a Increase in the threshold of hearing dB when wearing probed earplugs. Subjects 1 (top) and 3 (bottom)**




| | 250 | 500 | 1k | 2k | 3k | 4k | 6k | 8k | | 250 | 500 | 1k | 2k | 3k | 4k | 6k | 8k |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Left | | | | | | | | | Right | | | | | | | |
| Subject 6 O1 | 10 | 25 | 25 | 35 | 50 | 50 | 25 | 25 | | 5 | 20 | 35 | 30 | 40 | 35 | 35 | 30 |
| Subject 6 O2 | 25 | 30 | 25 | 40 | 50 | 45 | 45 | 40 | | 20 | 20 | 25 | 30 | 40 | 35 | 35 | 35 |
| Subject 6 O3 | 10 | 15 | 25 | 35 | 50 | 40 | 20 | 30 | | 5 | 20 | 30 | 30 | 45 | 30 | 35 | 40 |
| Subject 6 O4 | 10 | 25 | 20 | 40 | 45 | 55 | 25 | 50 | | 10 | 20 | 20 | 30 | 45 | 35 | 35 | 45 |
| Subject 6 O5 | 5 | 20 | 25 | 35 | 45 | 40 | 30 | 40 | | 5 | 20 | 30 | 30 | 45 | 30 | 35 | 30 |
| Subject 6 O6 | 25 | 30 | 25 | 40 | 50 | 45 | 40 | 35 | | 5 | 15 | 20 | 30 | 35 | 25 | 40 | 40 |




| | 250 | 500 | 1k | 2k | 3k | 4k | 6k | 8k | | 250 | 500 | 1k | 2k | 3k | 4k | 6k | 8k |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Left | | | | | | | | | Right | | | | | | | |
| Subject 7 O1 | -5 | 20 | 30 | 35 | 40 | 45 | 30 | 30 | | 5 | 20 | 20 | 30 | 45 | 40 | 35 | 45 |
| Subject 7 O2 | 0 | 10 | 15 | 25 | 25 | 25 | 15 | 20 | | 0 | 10 | 10 | 20 | 30 | 20 | 15 | 25 |
| Subject 7 O3 | 0 | 20 | 25 | 40 | 45 | 45 | 30 | 25 | | 0 | 20 | 25 | 35 | 50 | 45 | 25 | 50 |
| Subject 7 O4 | 5 | 25 | 20 | 35 | 30 | 40 | 15 | 20 | | 5 | 20 | 20 | 30 | 40 | 40 | 30 | 30 |
| Subject 7 O5 | 0 | 15 | 25 | 35 | 45 | 45 | 15 | 30 | | 25 | 35 | 30 | 45 | 60 | 60 | 55 | 55 |
| Subject 7 O6 | 5 | 20 | 20 | 30 | 40 | 40 | 20 | 45 | | 10 | 20 | 20 | 35 | 40 | 40 | 30 | 30 |

**Figure A2b Increase in the threshold of hearing dB when wearing probed earplugs. Subjects 6 (top) and 7 (bottom)**

# ANNEX B ADDITIONAL SUBJECTIVE SYSTEM TESTS

## B.1 MEASUREMENT PRECISION CHECK

A KEMAR head and torso simulator was used to determine the accuracy of the attenuation reported by the subjective system. The KEMAR was used as the subject. No earplugs were used but instead sound levels were set at each ear to simulate a specific attenuation value.

The sound levels at each ear were first set to be equal at each test frequency. When the system expected an earplug to be in the right ear the level in that ear was set to a specified number of decibels above the level in the left ear. When the subjective system expected earplugs to be in both ears the levels in each ear were again matched exactly at each frequency.

The reported PAR (Personal Attenuation Rating) value for each simulated earplug attenuation is shown in Table B1.

**Table B1 Reported PAR value for precise simulated attenuation**

| ***Simulated attenuation dB*** | ***Reported PAR value dB*** |
|---|---|
| -10 | -10 |
| 0 | 0 |
| 10 | 6 |
| 20 | 15 |
| 30 | 25 |
| 35 | 30 |

It is clear the system is de-rating the higher attenuation results by 5dB. The manufacturer confirmed this was intentional but did not give an explanation for the de-rating.

# ANNEX C HSL EQUIPMENT DETAILS

| Device | Serial number | Date of last calibration |
|---|---|---|
| KEMAR manikin | - | - |
| Brüel & Kjær (B&K) 4134 microphone in KEMAR ear | 799939 | 24 February 2010 |
| B&K 2639 microphone preamplifier | 1631078 | 18 February 2010 |
| B&K 2260 sound level meter | 2305154 | UKAS June 2009 |
| B&K 4226 calibrator | 1531353 | UKAS December 2009 |
| B&K 2804 microphone power supply | 684344 | n/a |
| B&K 3560-B Pulse module | 2517781 | Danak October 2010 |
| B&K 4190-C-001 TEDS microphone and preamplifier | 2510525 | 26 February 2010 |
| ASRA audiometer | 9459 | Calibration due April 2012 |

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# Assessment of subjective and objective measurement systems of earplug attenuation on an individual

Standard test methods to determine hearing protector attenuation use a real ear at threshold subjective method, where subjects identify when they can just hear test signals in order to establish their threshold of hearing. The threshold of hearing is measured over a range of test frequencies, with and without a hearing protector worn. The difference in threshold (with and without a hearing protector) provides the attenuation; and a group of results from a range of subjects provides a mean result and a standard deviation in each test frequency band.

Systems that measure earplug attenuation for individual wearers are commercially available and the work detailed in this report aimed to assess the performance and test the reliability of two types of available system: objective measurement and subjective equal loudness. Systems were chosen to represent a type of system rather than a specific model of device and because they: were commercially available through leading manufacturers; were designed for use by operators with a minimal level of training or expertise; could be used with a range of earplugs; and were typical of the state of the art.

Both systems investigated were found to have benefits and limitations. A number of recommendations are presented.

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