

Experimentation to Address Appropriate Test Techniques for Measuring the Attenuation Provided by Double ANR Hearing Protectors

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ABSTRACT

Increasingly the military environment can involve exposure to high levels of noise; levels of up to 150dB are anticipated (in some quarters) for deck-crew and ground-crew working with the Joint Combat Aircraft. In order to protect the hearing of personnel in high levels of noise, the use of double protection (earplugs worn in conjunction with earmuffs) is also increasing. Active Noise Reduction (ANR) systems are now widely incorporated into headsets and have also been incorporated into personally moulded earplugs. Therefore, the combination of an ANR Headset and ANR earplugs is the next obvious step in reducing high levels of noise at ear. Difficulties arise in determining the appropriate technique for establishing levels of sound attenuation achieved by the use of this Double ANR system. The Real Ear At Threshold (REAT) method has the advantage that it is a measure of the noise perceived by the subject. However, it can result in masking errors at low frequencies due to physiological noise. REAT cannot be used with ANR devices since the electronic noise of the ANR circuitry at approximately 1-2kHz will raise perceived threshold at this frequency range. The Microphone In Real Ear (MIRE) method has the advantage that it measures the absolute sound pressure levels in the ear canal and can be used with ANR devices. However, this technique does not necessarily measure what the subject hears, as it cannot measure the sound transmitted to the inner ear via routes other than the primary path of the ear canal.

The personally moulded earplugs used by QinetiQ have been designed to incorporate microphones at the tip to measure the sound pressure level within the ear canal, and the sense microphone of the ANR earplugs can also be used to measure the sound pressure level within the device. Experiments using ANR headsets in conjunction with passive personally moulded earplugs were used to compare REAT and MIRE methods and to show the differences between the techniques. The experimental results show that the overall attenuation provided by combinations of ANR headsets and passive earplugs can be found by choosing the appropriate technique in any given one third-octave band to produce a combined REAT/MIRE assessment of the attenuation.

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1.0 INTRODUCTION

Noise induced hearing loss is, in theory, entirely preventable and legislation [1, 2] exists to minimise and hopefully eliminate noise hazards and working practices that result in this type of hearing damage. The legislation provides limits on daily personal noise exposure and since the daily personal noise exposure is defined as a combination of noise level and exposure duration, the level can be traded against the duration to ensure that employees' personal exposure stays within the limits.

There are environments where the reduction of noise exposure by decreasing the noise level at source or by shortening the duration of exposure in order to comply with the legislative limits is impractical or costly to implement. These environments tend to be military, where the high levels of noise encountered by personnel are difficult to limit at source. In particular, the noise levels encountered by aircraft-carrier deck-crew, and potentially by ground-crew, are predicted in some quarters to be as high as 150 dB(A) when aircraft such as the Joint Combat Aircraft are brought into service. With noise levels this high, where a reduction in exposure duration by alteration in shift-patterns would result in unwieldy complements of personnel, the only remaining option in the reduction of noise exposure is to improve the hearing protection provided and thereby reduce the noise at the ear.

Standard hearing protectors, although improving in design and the levels of sound attenuation that they can achieve, do not sufficiently reduce the noise at the ear when working in these high noise environments. Hearing protection devices such as earplugs and earmuffs can be worn in combination to attempt to further reduce the noise travelling along the normal air-conductive pathways, i.e., down the ear canal, through the middle ear to the inner ear. However, the use of this type of double hearing protection does not increase the level of sound attenuation achieved by the sum of the attenuation provided by each device separately, as might be expected. The combined performance of the two devices is not simple to predict and although various empirical techniques have been used in the past to attempt to calculate the total attenuation achieved by double protection [3, 4] the most accurate method is still that of direct measurement.

One explanation for the failure of double protection to provide a level of sound attenuation equivalent to a summation of the separate attenuation levels is that at frequencies at and above 2kHz the limits of sealing the air conductive pathway have been reached. This means that at these frequencies any further addition of protection to the outer ear canal provides no extra benefit in reducing the noise dose received. Sound can also reach the cochlea via a number of routes through the head and torso, known as body or bone conduction, that were determined by Tonndorf [5] and have been investigated further by other researchers [6, 7, 8]. At low frequencies, vibration of the head causes the ear canal walls to vibrate and generate additional noise within the ear canal; this additional noise is transmitted to the cochlea via normal air-conductive routes. At higher frequencies the vibration of the bones and fluids of the head cause direct stimulation of the cochlea.

A number of researchers have investigated the bone conduction threshold i.e., levels of sound attenuation that are required before bone conduction pathways dominate the air conductive pathways. The highest bone conduction threshold was measured by Zwislocki [9], who achieved the high levels of attenuation in his experiment using metal rods and wax earplugs in combination with heavy earmuffs incorporating Helmholtz resonators. Watson and Gales [10] also established bone conduction thresholds using laboratory devices and Berger [11] showed that with double protection the insertion depth of a conventional earplug influenced the level of overall sound attenuation regardless of the weight and type of earmuff. These researchers all established different bone conduction thresholds.

The combined use of standard earplugs and earmuffs produces levels of hearing protection that reach bone conduction limits at the higher frequencies, however, at lower frequencies the bone conduction limits are not met. Following on from Berger's work with deeply inserted foam earplugs, some researchers are developing personally moulded earplugs that extend down into the bony meatus, thereby reducing the vibration of the ear canal walls at low frequencies. An alternative approach is to increase the protection provided by the earplug and earmuff, by using high quality passive devices incorporating Active Noise Reduction (ANR) systems. ANR provides extra active attenuation below 1kHz and the extra active attenuation in the ANR earmuff and the ANR earplug may enable the noise at the ear to be reduced further, increasing levels of attenuation until the bone conduction thresholds are met at all frequencies.

The Royal Aerospace Establishment developed a universal-fit ANR earplug [12] in which a t-shaped device was fitted through a shortened foam earplug. This ANR earplug contained a microphone that sensed the sound pressure level in the ear canal and a transducer that emitted the ‘cancelling’ waveform. The earplug was connected via a thin cable to an external box that contained the ANR circuit. Although the ANR earplug worked well it was difficult to wear comfortably under earmuffs, as the top section did not fit well into the subjects’ conchas.

Further development of the ANR earplug by QinetiQ has produced a unique-fit device that is personally moulded to the subject’s own ears. In this form, the earplug is easy to fit but can still contain the ANR sense microphone and the transducer to emit the cancelling noise. As before, a thin cable connects the earplug to the external ANR system. This device is still a prototype and materials used in the construction have not been optimised for either their sound attenuating properties or comfort. However, since the earplug has been moulded to the subject’s ears, the occurrence of friction or pressure hot-spots is greatly reduced compared to the universal-fit model.

In order to facilitate the research into the combination of the ANR earplug and an ANR earmuff, a number of personally moulded earplugs have been manufactured that contain an additional miniature microphone positioned at the tip of the earplug, which will be positioned in the ear canal itself. The electronics have also been modified so that the ANR sense microphone, used to measure sound pressure level for the ANR system, can be read by the experimental operator. This means that the personally moulded ANR earplugs have two microphones that can be used for observation of the sound pressure level within the earplug and within the ear canal.

The headset chosen for use during this research is a Peltor Optime III device that has high levels of passive sound attenuation. One of these Peltor headsets was fitted with a high quality ANR system that has been proven in other types of earshell and that is currently being flown by the UK Royal Navy.

A full range of experiments investigating the sound attenuation achieved by a personally moulded passive earplug, the personally moulded ANR earplug described above, a Peltor Optime III headset and the modified Peltor ANR headset are described in a companion paper [13]. The following sections of this paper examine the validity of two common measurement techniques used to determine the sound attenuation afforded by double ANR protection.

2.0 MEASUREMENT TECHNIQUES

Two different techniques are widely used to determine the sound attenuation of different types of hearing protector. The Real Ear at Threshold (REAT) technique uses a human subject to detect their threshold of hearing when no hearing protection is worn (unoccluded) and with the hearing protector in place (occluded). This method can be used with all types of passive hearing protectors, including earmuffs, headsets and earplugs since it is reliant on the subject’s perceived change in threshold and not on any instrumentation. The second technique, known as Microphone in Real Ear (MIRE), uses miniature microphones that are mounted either into the earmuff of a hearing protector using clips or by fixing them at the entrance to the ear canal of a subject [14]. A noise field is generated and the noise level at the microphone is measured both with and without the hearing protector in place. The subject in this case is purely used as an accurate ‘dummy’ head and the inter-subject variation in the measured sound attenuation will be due to the difference in the fit of the hearing protector on the individual. The location of the microphone (in the earmuff or in the ear canal) can provide different sound attenuation figures for the same hearing protector; however, if the same location is used throughout an experiment, the results are highly repeatable across subjects and provide lower standard deviations than exhibited using the REAT technique. Microphones can also be placed on the occluded side of an earplug to perform MIRE as long as sufficiently small microphones and very narrow wires are used to connect the microphone to the instrumentation.

REAT has the advantage over MIRE in that the sound attenuation determined by this technique is what the subject hears, regardless of how the sensation of hearing is generated. However, at low frequencies (particularly at 63 Hz and to a lesser extent at 125 Hz) physiological noise due to the noise of blood flow and the pulsing of the blood at heartbeat frequencies produces masking effects. This masking noise is noticeable when the ear is occluded and is known as the occlusion effect. Since the masking does not occur when the ear is unoccluded, at low frequencies REAT will over-estimate the sound attenuation of a device [15]. Additionally, REAT cannot be used with ANR devices since the residual noise generated by the active noise system will also cause masking at some frequencies up to 2kHz and will therefore raise thresholds and again over-estimate the sound attenuation achieved. REAT can, of course, be used with standard passive earplugs and with ANR devices that are not used in their active mode, i.e. with the active system turned off. REAT will also measure the sound that reaches the cochlea via bone conduction pathways. However, since REAT is performed at threshold, whereas MIRE is measured in a sound field at high noise levels, REAT assumes that the hearing protector is linear with increased noise level, in order that the sound attenuation measured at threshold will still be valid at higher noise levels.

MIRE measures the sound pressure level in the ear canal or within the earmuff, not at the cochlea. Therefore the effects of blood flow and bone conduction are ignored. It has the advantage over REAT that it can be used with ANR, since MIRE measurements are made in high ambient noise levels that greatly exceed the masking produced by the residual noise of the active system. The main disadvantage of MIRE over REAT is that it does not necessarily measure what the subject hears, since it misses the contribution from the bone conduction pathways. Hence, at higher frequencies MIRE will over-estimate the sound attenuation.

3.0 EXPERIMENTAL PROCEDURE

3.1 Measurement Facility

QinetiQ have a high noise facility that has been used to measure sound attenuation by MIRE for many years. The facility and techniques used to measure sound attenuation by this method follow ANSI S12.42 1995 [16]. Recently, the facility has been upgraded so that measurements can be taken by the REAT technique in accordance with ANSI S12.6 1997 [17]. The capability has also been extended so that as well as recording threshold levels at the frequencies set out in the standard REAT method, thresholds can be measured across the whole third-octave spectrum at centre frequencies from 50Hz to 12kHz. This enables REAT results to be compared with MIRE results in all one third-octave bands, or to pursue detailed investigation of REAT at frequencies of interest.

An extensive range of measurements using combinations of ANR earmuffs and passive and ANR earplugs have been undertaken, and a full description of these measurements and results are provided in the companion paper [13]. In order to examine the effect of the measurement technique, only a small number of these measurements are examined in this paper.

3.2 Measurement of ANR Residual Noise

In order to establish the level of residual noise generated by the personally moulded earplugs, a measurement was taken of each earplug fitted in turn to a Brüel and Kjær (B&K) artificial ear type 4153. The artificial ear was located within an Anechoic Chamber and the earplugs were sealed to the artificial ear using a re-useable adhesive putty, taking care to prevent leakage and any associated feed-back within the ANR system. This provided the frequency range over which the residual noise was generated by each system, and thus indicates the frequencies at which REAT measurements should not be attempted with an ANR system in active mode. The sound pressure levels measured by this method will not correspond to

those encountered on the ear, since the volume that the system is working into on the artificial ear will be different from that on the human ear.

3.3 MIRE measurements

The MIRE measurements in these experiments were conducted on each of the subjects seated in a diffuse noise field of 120 dB(A) and wearing a combination of the passive and active earplugs and earmuffs. The sound pressure level at several points along the sound transmission path into the ear canal was measured with a series of microphones, as shown in Figure 1. The microphones either side of the earmuff, labelled microphones 1 and 2, are not discussed in this paper. The measurement positions of interest are microphone 3, the ANR sense microphone, and microphone 4, referred to as the probe microphone. The probe microphone is not positioned deeply in the ear canal and does not necessarily record the sound pressure level achieved at the tympanic membrane. MIRE measurements were obtained on Brüel and Kjaer 2133 Dual Channel Frequency Analysers, taking a 16 second average when the signal in the room had become stationary, over the frequency range 31.5 Hz to 10 kHz. One measurement was taken at each microphone for each combination of hearing protectors.

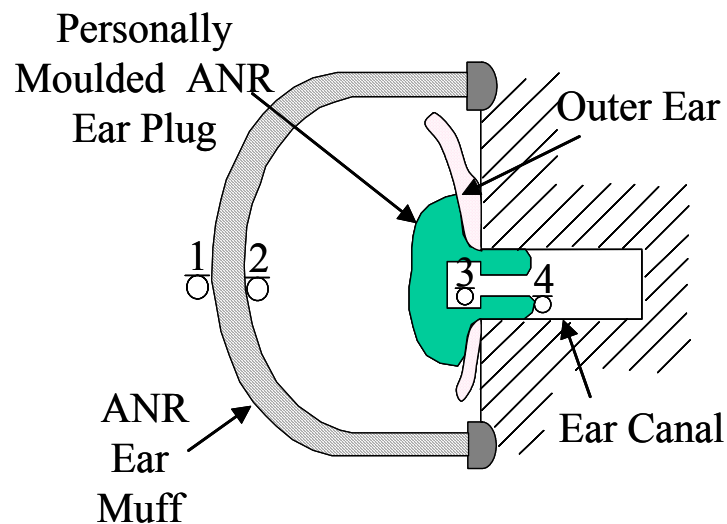


Figure 1: Measurement Microphone positions for MIRE with double ANR hearing protection. Microphones measure the SPL at: 1) the unoccluded field, 2) within the earmuff, 3) at the ANR sense microphone and 4) within the ear canal.

Since the ANR sense microphone and the probe microphone are embedded within an earplug, a method of achieving an unoccluded measurement had to be determined. The microphones from each earplug could obviously not be removed and placed in their respective positions at the entrance to the subject's ear canal and within it without destroying the earplug. One approach was to measure the sound pressure level with the earplugs suspended in the sound field at head height, disregarding any influence of the ear and head on the unoccluded sound field. A second method was to locate the earplug in an artificial ear canal, made of a 30mm length of aluminium tubing, 10 mm in diameter with walls 1 mm thick, and suspend this combination within the unoccluded sound field. However, this approach best approximates microphones that are positioned at the tympanic membrane, not at the open entrance to the ear canal.

The provision of the two microphones, the ANR sense microphone and the probe microphone located in the ear canal, enabled a comparison of the MIRE attenuation at each position. The probe microphone on these earplugs is easily fitted when the earplug is inserted and is located in a repeatable position. The wire leading from the earplug was taken over the top of ear, passing behind the ear and following the

depression between the jaw and the mastoid bone. This reduced the breakage of the acoustic seal of the headset to a minimum. The double ANR protection is shown in Figure 2 on a B&K Head and Torso Simulator for clarity.



Figure 2 Double ANR protection, cut-away shows personally moulded earplug and position of cable, minimising acoustic leakage.

The sound attenuation was measured for the personally moulded ANR earplug alone and in combination with the ANR headset. The ANR system of either device could be activated or the system left in its passive mode and the combinations discussed in this paper are:

- a) ANR headset passive, ANR earplug passive
- b) ANR headset passive, ANR earplug active

The ability to measure the systems in their passive mode is important for comparison with REAT measurements. The results of the attenuation measured by MIRE at the sense and the probe microphones for the ANR earplug alone and in combination with the ANR headset passive are reported here.

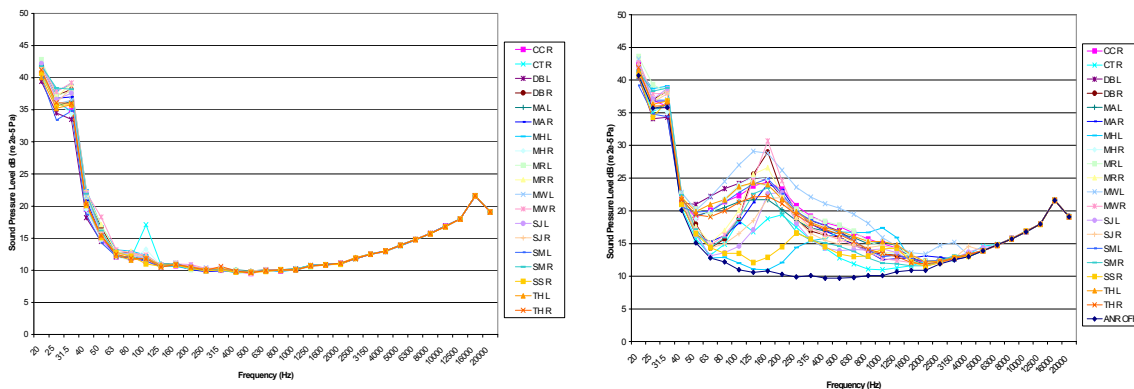
3.4 Comparison of MIRE and REAT measurements

REAT measurements were also undertaken for the same combinations of passive and active earmuffs and earplugs as for the MIRE measurements. Although REAT was not measured for the ANR earplug in its active mode, the ANR earmuffs could be used when active, since the earplug prevented the residual noise being heard by the subject. Therefore, the combination (a) above was also measured using REAT over an extended number of third-octave bands. As we were particularly interested in whether the limits of bone conduction had been reached, REAT was performed at the centre frequencies required by the standard test method (125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz and 8 kHz) with the addition of the third-octave bands centred on 63 Hz and at 2.5 kHz, 3.15 kHz, 5 kHz, 6.3 kHz, and 10 kHz. An experimenter-supervised fit was used throughout and one REAT measurement performed for each combination of hearing protectors.

4.0 RESULTS AND ANALYSIS

4.1 ANR Residual Noise

The measurements of the residual noise produced by the personally moulded ANR earplugs when positioned on the artificial ear are shown in Figure 3. The measurements indicate that about half of the earplugs generate an ‘electronic hiss’ over the frequency range 50 Hz to 2 kHz, with a similar number generating noise over the slightly narrower band of 80 Hz to 2 kHz. Two earplugs only generate the noise from 160 Hz to 2 kHz and therefore do not exhibit a peak level at the same frequency as the other earplugs. For the majority of the earplugs, the maximum noise is generated at 160 Hz. The range of frequencies of the residual noise corresponds to the low frequencies that the ANR system is designed to reduce, centred on the particular frequency of 160 Hz, and extends up into the mid-frequency range into those regions where ANR systems reinforce or enhance the noise.



Figures 3a and 3b Sound pressure level produced by personally moulded earplugs mounted on an artificial ear. a) ANR system off and b) ANR system on.

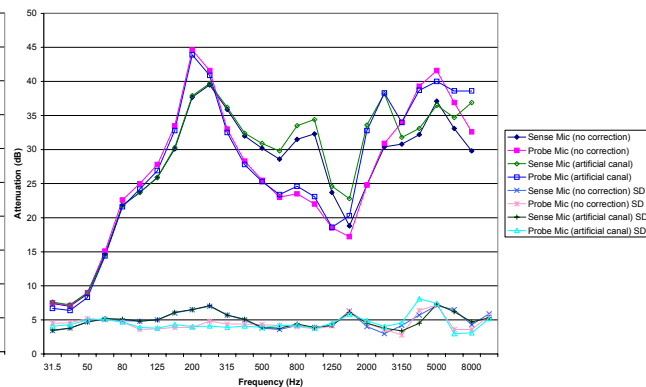
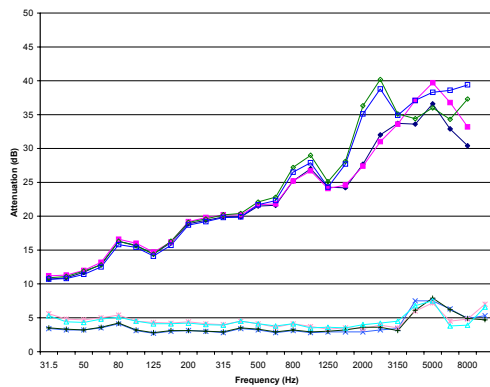
Hence, the REAT technique cannot be used with these personally moulded ANR earplugs at frequencies below 2 kHz, as the residual noise of the system will produce masking and therefore over-estimate the sound attenuation provided by the earplug at these frequencies.

4.2 MIRE measurement microphone

The levels of attenuation achieved by the ANR earplug were measured using the MIRE technique for the earplug in its passive and its active modes of operation. In order to calculate the attenuation, the sound pressure level measured in the occluded ear should be subtracted from the sound pressure levels measured with the ear unoccluded.

Figure 4 illustrates the differences in attenuation achieved using the different methods of measuring the unoccluded sound field for the ANR earplugs in their passive and active modes. The curves are the mean of the attenuation calculated for various numbers of subjects; with ANR off, sense microphone (18 ears out of a maximum 20 ears, i.e. 10 pairs of ears), probe microphone (17 ears), with ANR on, sense microphone (16 ears) and probe microphone (14 ears). Measurements were not taken for those subjects where the microphone failed to work and for those for whom the ANR produced feed-back when switched on. These were caused by failures in the manufacture of the earplugs and the feedback was caused by an incomplete acoustic seal of the earplug in the ear canal. Several attempts were made to re-set those earplugs generating feed-back, however, it was not always possible to prevent feed-back from occurring, suggesting errors in the moulding of the earplug.

Figure 4a shows a distinct peak in the response at 2500 Hz for the passive attenuation data corrected by the artificial ear canal. This peak corresponds to the resonance of the artificial ear canal. A similar peak can be seen in Figure 4b for the attenuation with the ANR system on. There are differences between the sense and the probe microphone at frequencies above 3.15 kHz but these occur for both the ANR off and on, with and without the use of the artificial ear canal and are likely to be due to the difference in the position of the sense and probe microphones.



Figures 4a ANR off **Figure 4b ANR on**
Mean attenuation and SD for ANR earplug measured at Sense and Probe microphone positions. Unoccluded measurement in free field corrected by use of an artificial ear canal and not corrected.

When the ANR system is activated, the differences between the position of the ANR sense microphone and the probe microphone become more apparent. The peak in the ANR response is at 200 Hz for both microphones, but the sense microphone shows an additional peak between 800 Hz and 1 kHz. The probe microphone has a minor increase in the attenuation in this region, as do both microphones when measured with the ANR system off. The slight peak in the region of 800 Hz is not particularly noticeable on the sound pressure level data used to obtain the unoccluded condition and so may be an occlusion effect within the ear canal. However, when the ANR system is off the difference between the sense and probe microphone at this point is negligible; with the ANR system active, the peak at the sense microphone becomes much larger than the peak for the probe microphone. The difference between the sound pressure levels at the two microphones is primarily a function of the positions of the microphones and the operation of the ANR system. The ANR has been optimised at the sense microphone position, so the best measure of the sound attenuation achieved by the system will be at the sense microphone. The probe microphone measures the sound attenuation in the ear canal and the difference between the measurement at this position and at the sense microphone provides an indication of the effectiveness of the ANR beyond the earplug. The constriction of the ear canal portion of the earplug also acts as a low-pass filter and this will also reduce the effectiveness of the ANR within the ear canal. Since the probe microphone is only located part-way into the ear canal, it is not measuring the sound pressure level at the eardrum and so the acoustics of the ear canal itself may be influencing the levels of attenuation measured.

An attempt was made to further investigate the differences between the sense microphone and the probe microphone. Personally moulded earplugs had also been manufactured for a B&K Head and Torso Simulator (B&K HATS); of these, the left earplug did not appear to function correctly. Figures 5a and 5b show the attenuation achieved on the B&K HATS with the Right personally moulded ANR earplug. The attenuation determined at each microphone should provide an indication of what is causing the differences. The curves for the probe microphone and for the microphone located within the B&K HATS at the ‘eardrum’ have an almost identical response. This is due to the short length of the ear canal within the B&K HATS, which results in the probe microphone being positioned very close to the ‘eardrum’

microphone. The sense microphone curve is approximately 5 dB below that of the probe microphone curve up to 2 kHz, as shown in Figure 5a for the ANR in passive mode. This off-set does not occur on the human subjects, where in the passive mode the earplug sense and probe microphones provide very similar results (Figure 4a).

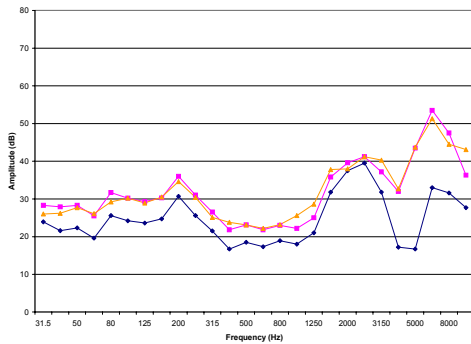


Figure 5a ANR off

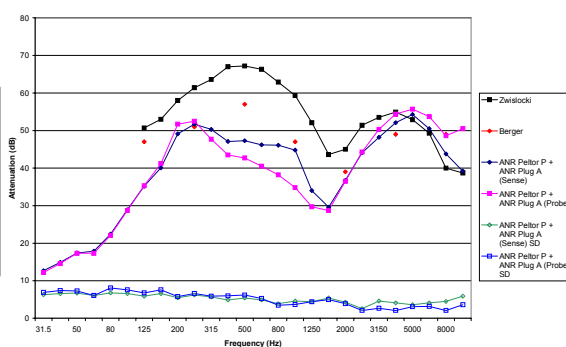
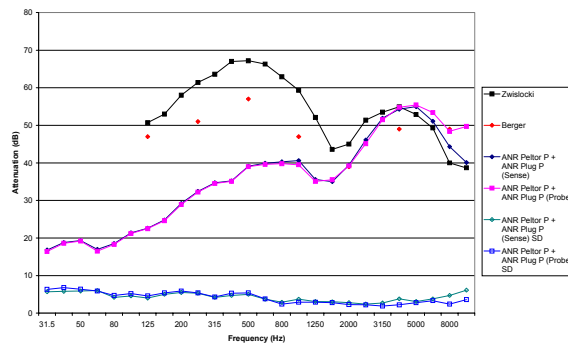
Attenuation achieved measured by MIRE on B&K HATS using Personally moulded ANR earplug

Figure 5b ANR on

Attenuation achieved measured by MIRE on B&K HATS using Personally moulded ANR earplug

The peak in the attenuation for all three microphones on the B&K HATS is at 200 Hz and this is a function of the electronics in the ANR system. The difference in the frequency range of the attenuation with the ANR system active for the HATS and for the human subjects may be due to the differences in the ear canal of the human subjects compared to the simulated canal of the HATS. The ANR sense microphone again provides higher levels of attenuation at frequencies greater than the ANR centre frequency compared to the probe microphone, which is indicative of the low-pass filter effect caused by the constriction in the earplug through the ear canal portion, which is particularly noticeable when the ANR is active.

The attenuation measured by MIRE for the combinations of the passive ANR Peltor headset worn together with the personally moulded ANR earplugs in Passive and Active mode are shown in Figures 6 a) and b). The MIRE attenuation was again measured at both the sense and the probe microphones, but in the graphs below only the measurements with the uncorrected ear canal data have been shown. The attenuation data when the artificial ear canal was used for the unoccluded measurement provided a higher level of attenuation around 2.5 kHz and so the uncorrected version gives lower attenuation, even though this may be an underestimate of the total attenuation provided by the double protection. The curves for the bone conduction thresholds of Zwislocki [9], achieved by uncomfortable laboratory techniques, and for Berger [11], achieved by the use of deeply inserted E.A.R. foam earplugs together with a headset, are given for comparison.



Figures 6a ANR Headset Passive and Active with ANR earplug Passive **Figure 6b ANR Headset Passive and Active with ANR earplug Active**
Attenuation of Double ANR system using MIRE. Measured at probe and sense microphones with no correction applied to unoccluded measurement.

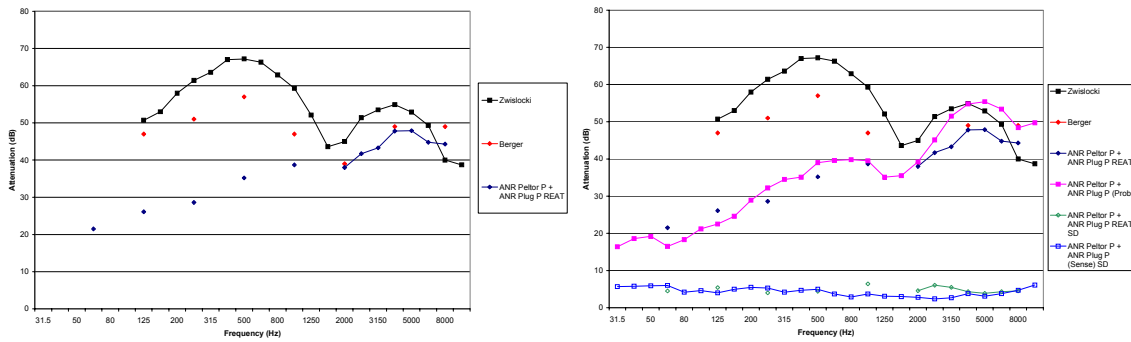
The passive ANR Peltor headset plus passive ANR earplug is a mean of 18 measurements (i.e. 18 different ears) for the sense microphone and 16 measurements for the probe microphone. The passive ANR Peltor headset plus active ANR earplug is a mean of 15 measurements for the sense microphone and 14 measurements for the probe microphone. Again, measurements were excluded for those earplugs where the microphone did not work and where activation of the ANR system resulted in feedback in the ear canal.

The differences between the sense and the probe microphones are again most noticeable around 1 kHz when the ANR earplug is in its active mode, whereas the differences at 3.15 kHz are much less when using double protection than when the earplug is worn alone. The combination of the ANR headset and active ANR earplug reaches the limits of bone conduction set out by Berger at 200 to 250 Hz for both the probe and the sense microphone. At 1 kHz the sense microphone also shows levels of sound attenuation that reach Berger’s bone conduction limits. The ANR system has been optimised at the sense microphone, which suggests that if the ANR system could be optimised at the probe microphone rather than at the sense microphone the bone conduction thresholds could be achieved over a broader frequency band.

For both cases, with the ANR earplug passive and active, the MIRE measurement shows levels of attenuation greater than the bone conduction limits of Zwislocki and of Berger at frequencies above 2 kHz.

4.3 Comparison of MIRE and REAT measurements

For double ANR protection, the MIRE measurements show that the bone conduction limits at mid to high frequencies have been exceeded. However, the MIRE technique cannot measure the sound reaching the cochlea by bone conduction routes at frequencies above 2 kHz. Therefore, a similar set of measurements was performed using REAT and Figure 7a shows the attenuation achieved by REAT under the ANR Peltor headset and the personally moulded ANR earplug both operating in their passive modes. This is the mean of the results for 10 subjects. A comparison of the REAT measurement and the MIRE probe microphone measurement for this condition is shown in Figure 7b.



Figures 7a REAT with ANR Headset Passive and Active and ANR earplug passive Figure 7b comparison of REAT with MIRE
Attenuation of Double ANR system

The graph of attenuation measured by REAT reaches the limits of bone conduction as set out by Berger between 2 kHz and 5 kHz. The comparison with the MIRE technique shows that this method is over-estimating the attenuation because it cannot measure the sound transmitted via bone conduction. A t-test performed on the results of these two techniques shows that there is a significant difference between the methods above 2.5 kHz ($p=0.0009$, $\alpha=0.05$). Below 2 kHz, MIRE produces slightly higher levels of sound attenuation between 200 Hz and 2 kHz than REAT, although these differences are only 4 dB. The t-test shows a significant difference between the methods at 250 Hz and 500 Hz ($p=0.045$, $p=0.025$, $\alpha=0.05$), but no difference at 1 kHz, 2 kHz and 2.5 kHz. At 63 Hz and at 125 Hz REAT produces higher levels of sound attenuation than MIRE, which is due to the physiological noise produced in the ear canal when occluded and is a function of this technique. However, the t-test analysis of the results shows that there is no significant difference between the two methods at these two frequencies ($p=0.083$, $p=0.091$, $\alpha=0.05$).

5.0 MEASUREMENT OF ATTENUATION: REAT VS MIRE

The introduction of active noise reduction into headsets and earplugs has resulted in difficulties in choosing the correct technique to measure the levels of sound attenuation actually experienced by a human subject. The two techniques open to the investigator have their own peculiarities and present different difficulties in interpretation. The influence of bone conduction on the levels of attenuation achieved as experienced by the subject suggests that REAT is the better technique, however, the problems of masking presented by the residual noise of the ANR system lead to the choice of the MIRE technique.

It has been suggested that REAT should be used to determine the level of attenuation achieved when the ANR system is in its passive mode (i.e. the ANR system is turned off), and that the effect of the ANR system as measured by the MIRE technique should be added to this to present the total attenuation at the ear. This results in the device under test being measured three times per subject, once for REAT with the ANR system off and twice for MIRE with the ANR system off and on. It is the difference between the two MIRE measurements that produces the purely ‘active’ attenuation that is added to the passive REAT data. REAT is usually measured at the centre third-octave of an octave band, whereas MIRE can be measured at third-octave bands covering the whole frequency spectrum. MIRE is a faster technique than REAT, requiring only tens of seconds to complete a single measurement, however, it seems excessive to acquire this data only to ignore two thirds of it. With current hearing protection devices used singly, the limits of bone conduction are not met and so it would seem that MIRE alone would be sufficient to provide the attenuation due to an ANR device.

The attenuation provided by double hearing protection, e.g. a headset and earplug in combination, will result in the bone conduction limits being met at frequencies above 2 kHz. The residual noise of the ANR

system used in the personally moulded earplugs extended up to 2 kHz, which corresponds to those frequencies where the ANR system reduces the sound pressure level in the ear canal and those frequencies where the ANR system reinforces and thereby increases the sound pressure level in the ear canal. Although MIRE provides the best measure of attenuation below 2 kHz, above 2 kHz it is probable that REAT should be used. If the decision to use two techniques has already been taken, as mentioned above, it may perhaps be an improvement to use different techniques over different parts of the frequency spectrum. Therefore, it would seem appropriate to use MIRE to measure the sound attenuation at frequencies up to 2 kHz and for REAT to be used at frequencies above 2 kHz.

However, the difficulty of choosing the position of the microphone with which to perform the MIRE measurements now becomes significant. If the ANR system under test is an earplug, the sense microphone could be used for the measurement if the electronics allows the microphone signal to be tapped, as shown in these experiments. This may over-estimate the levels of attenuation achieved by the device, as it will measure the sound pressure level when optimally reduced. If the ANR sense microphone cannot be used, then a microphone must be positioned within the ear canal with the signal fed back underneath the earplug by a means that does not compromise the acoustic seal. As has been shown already in this paper, the results produced by the sense microphone and the probe microphone seated in the ear canal can be significantly different over parts of the frequency spectrum. If the ANR sense microphone does not provide a measure of the sound pressure level at the eardrum, then MIRE will not give a correct indication of the attenuation experienced by the subject. If the probe microphone, situated in the ear canal, is located at a position where the ANR system is not reducing the sound pressure level sufficiently, this microphone will not give a true indication of the attenuation experienced by the subject.

6.0 CONCLUSIONS

The measurement of the sound attenuation provided by ANR devices worn in combination leads to conflicting decisions when choosing the measurement technique. The use of REAT is not possible at those frequencies when the ANR system produces masking noise. On the other hand, the likelihood of reaching the limits of bone conduction above 2 kHz precludes the use of MIRE. As a result of experiments on human subjects together with a unique personally moulded ANR earplug incorporating two measurement microphones, it is suggested that MIRE should be used to obtain the attenuation below 2 kHz and that REAT should be used above 2 kHz. Further investigation should be undertaken into the location of the microphone for MIRE.

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