Investigating Double Hearing Protection using Human Subjects

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ABSTRACT

In the increasingly noisy military environment and with the growing need to protect the hearing of military personnel, the use of double protection, earplugs and earmuffs used in combination, has become more and more prevalent. Furthermore Active Noise Reduction (ANR) headsets and earplugs appear to offer a means of increasing the attenuation of these double protection systems. However, it has been shown that the attenuation afforded by double protection is not a simple additive process, the combined attenuation tends to be less than the sum of the individual earplug and earmuff attenuation figures. Also, at the levels of attenuation provided by double protection, bone conduction pathways start to play an important part in the sound level received at the ear. A fuller understanding of these processes is required if the full benefit of double protection is to be achieved in future devices.

Most previous assessments of the attenuation the afforded by double protection and bone conduction limits have been carried out using the REAT (Real Ear At Threshold) test technique. However, this technique is limited for predicting the attenuation from active systems due to the masking effect of the residual electronic noise. Other work has used ATF (Acoustical Test Fixtures) for predicting the attenuation provided by ANR double protection. However, this can only take into account bone conducted noise by the use of mathematical models. The study presented here employed both REAT and MIRE (Microphone In Real Ear) test techniques to investigate the attenuation given by both passive and active noise protection devices when used in combination. The MIRE experimentation was carried out in noise fields up to 120dBA and the sound pressure level, in the earshells and ear canals, was monitored via miniature microphones and probe microphones fitted in personally moulded earplugs respectively. The study included testing on ten subjects, where all the hearing protectors were fitted as they would be used in the field. The MIRE and REAT experiments have both shown that headsets with varying performance of attenuation appear not to have a major effect on the overall attenuation when worn over earplugs and it is the performance of the earplugs that has a more direct effect on the attenuation of the double protection system. However, from direct measurements of the Sound Pressure Level (SPL) under the earmuffs during the MIRE procedure it can be concluded that the attenuation of the earmuff remains constant, implying that there is an interaction between earmuff and earplug that is leading to the degradation of the attenuation afforded by the double protection system.

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1.0 INTRODUCTION

The noise environment that military personnel are subjected to is becoming increasingly harsh, with noise levels to which aircrew are exposed rising from 110 dB to a maximum of 120 dB in the last thirty years. Fortunately, the optimisation of passive hearing protectors and the introduction of active noise control systems have meant that the ability of personal hearing protection to reduce noise at the ear has kept pace with the increased noise risk.

In future aircraft, such as the Joint Combat Aircraft (JCA) and Euro Fighter (EF) Typhoon, the noise levels in the cockpit are expected to increase only marginally. However, deck-crews and possibly ground-crews will be exposed to the environmental noise generated by these aircraft and the noise levels to which they will be exposed are predicted in some quarters to be as high as 150 dB. At these noise levels single protection earmuffs or earplugs worn alone will not provide sufficient attenuation to bring noise dose within legislative criteria. Double protection systems, earplugs and earmuffs worn in combination, are the obvious answer to increase the attenuation afforded. However, double protection is a complex process and the overall attenuation is not the addition of the two single protector attenuations. Various empirical techniques have been used to attempt to calculate the total attenuation achieved by double protection [1][2], but the most accurate method is still that of direct measurement.

One of the factors that has been found to limit double protection systems is bone conduction (BC), sound reaching the cochlea by pathways other than the standard air conduction (AC) pathway via the ear canal. The limiting effect occurs when the BC influence becomes greater than that of the AC pathway, i.e. when the air conducted pathway is sufficiently occluded. It has been found that above 2kHz earplugs and earmuffs worn in combination are sufficient for bone conduction limits to be reached [3][4][5]. This explains, at these frequencies, why the simple addition of single hearing protector attenuations does not result in the overall attenuation measured. At the lower frequencies it has been conjectured that the limitation of attenuation is the mechanical coupling between the earplug and earmuff [3]. More over it has been found that the individual attenuation of a headset worn over the earplug does not effect the overall attenuation [4][6][7], i.e. a poor attenuating headset or a good attenuating headset worn over the same earplug gives the same overall performance. Behar and Kunov [6], in their work, found for poor attenuating earplugs there was no advantage given by better hearing protector attenuation but for good attenuating earplugs, the attenuation of the headset did benefit the overall attenuation. However, this work used an Acoustical Test Fixture (ATF) that does not monitor bone conduction and no corrections were made to take account of it.

Therefore to further increase hearing protection performance, bone conduction has to be considered. Tonndorf identified three specific bone conduction pathways [8]:

- External ear component of bone conduction: the external ear canal walls vibrating cause pressure perturbations in the ear canal, which then excites the eardrum in the standard manner.
- Middle ear component of bone conduction: the inertial vibrations of the ossicles (middle ear bones).
- Inner ear component of bone conduction: mechanical distortion of the cochlear walls.

The external ear component has been identified as the dominant pathway below 2kHz, when the ear canal has been occluded at it’s entrance [9][10]. This effect has been termed the occlusion effect, as when the ear is unoccluded the ear canal acts as a high pass filter, which reduces the external ear BC pathway at low frequencies [8]. Stenfelt et al. identified this component of bone conduction to be specifically the oscillation of the soft ear canal tissue as opposed to the bony portion of the ear canal. Deeply inserted earplugs (inserting into the bony portion of the ear canal) circumvents this effect [3][4]. Above 2kHz and when the ear is unoccluded, the middle ear and inner ear pathways are dominant. However, the relative effect of the two pathways is hard to attain.

The main aim of the current study was to investigate the effect of Active Noise Reduction (ANR) systems when used in double protection systems. Berger et al. [7], used an ANR headset in active mode over deeply inserted earplugs and found a statistically significant increase in attenuation as compared to the ANR off mode, but questioned practical benefit of the increase. For the current study the ANR headset system chosen for use in the testing of double protection systems was a Peltor Optime III, modified with a production ANR system that is currently in use in flight helmets worn by UK Navy Aircrew.

In previous work the highest low frequency BC limits were reached using deep inserted earplugs, because as mentioned these circumvent the external ear BC pathway. ANR earplugs provide a possible method for attaining higher levels of attenuation, close to previously found BC limits, without the impracticality of deep inserted earplugs. The Royal Aerospace Establishment (RAE) developed a 'top-hat' style ANR capsule that was fitted into the ear through a shortened standard foam earplug [11]. Although this device worked well, the earplug did not sit well under a headset and was therefore uncomfortable when used in double protection. QinetiQ have now developed the design so that now a personally moulded earplug is used to house the ANR components and these fit more comfortably under earshells.

The work reported in this paper presents the attenuation data attained for double protection systems from both the objective Microphone In Real Ear (MIRE) method [12] and the subjective Real Ear At Threshold (REAT) method [13]. MIRE was used because REAT cannot measure "direct" ANR performance due to the residual electronic noise of these systems. REAT was used because MIRE does not take into account the middle and external ear BC pathways because it only measures the sound pressure level in the ear canal. A full discussion of the measurement techniques is presented in a companion paper [14].

2.0 EXPERIMENTATION

In order to investigate the protection provided by double protection a number of experiments were devised to measure the levels of sound attenuation afforded by these devices. These experiments involved four individual hearing protection devices, a passive and an ANR headset and a set of passive and ANR earplugs (see Table 1). Two independent experiments were carried out to calculate the attenuation of the hearing protectors worn both singly and in combination (earplugs + headset). The first experiment was based on an objective microphone method and the second experiment based on a subjective method. The microphone method uses the MIRE (Microphone In Real Ear) standard ANSI S12.42 1995 [12] and the subjective method uses the REAT (Real Ear At Threshold) standard ANSI S12.6 1997 [13]. The REAT method has been extended to include all of the third-octave bands from 50Hz to 12.5kHz, to allow direct comparison with MIRE results.

Hearing protector	Type	Graph Key
Peltor Optime III	Passive Headset	Passive HS
Modified Peltor Optime III	ANR Headset	ANR HS (off/on)
Personally moulded passive earplug	Passive Earplug	Passive EP
Personally moulded ANR earplug	ANR Earplug	ANR EP (off/on)

Table 1: Hearing protectors used

The signal from the ANR sense microphone in the ANR earplugs could be accessed by the experimenter and the ANR earplugs were also designed to incorporate an additional microphone located at the 'tip' of the earplug, positioned within the ear canal (see Figure 1). This additional microphone is known as the 'probe' microphone as it measures the actual sound pressure level experienced in the ear canal. The signals from both microphones were fed along a thin cable, routed over the subject's ear and down through the depression between the subject's jaw and mastoid bone. Therefore, when the earplug was worn underneath a headset, the cable did not break the acoustic seal of the headset.

Passive versions of the personally moulded earplugs were also made for each subject. These contained a ‘probe’ microphone in the same location as for the ANR earplug, but did not contain any ANR components. The cable from the probe microphone was routed around the subjects’ ears as described above.

2.1 MIRE Experimental Procedure

The laboratories at QinetiQ have a custom built reverberation chamber that allows generation of a diffuse sound field up to 120dB(A). To asses the attenuation of the hearing protection over a range of noise levels measurements were made at five noise levels, from 80dB(A) to 120dB(A) in 10dB(A) steps. A diffuse pink noise field was used, which has a flat 1/3 octave band spectrum.

Measurement No.	Measurement Condition
0	Noise field calibration, with BK4134 mic. at the centre of subject head position.
1	Passive Earplug: Probe mic. unoccluded in free field, at the five noise field levels
2	Passive Earplug: Probe mic. unoccluded in "ear canal simulator", at the five noise field levels
3	ANR Earplug: Probe, Sense mics. unoccluded in free field, at the five noise field levels
4	ANR Earplug: Probe, Sense mics. unoccluded in "ear canal simulator", at the five noise field levels
5	Passive Headset
6	Passive Earplug
7	Passive Earplug + Passive Headset
8	Passive Earplug + ANR Headset (off)
9	Passive Earplug + ANR Headset (on)
10	ANR Headset (off)
11	ANR Headset (on)
12	ANR Earplug (off)
13	ANR Earplug (on)
14	ANR Earplug (off) + ANR Headset (on)
15	ANR Earplug (off) + ANR Headset (off)
16	ANR Earplug (on) + ANR Headset (off)
17	ANR Earplug (on) + ANR Headset (on)
18	ANR Earplug (off) + Passive Headset
19	ANR Earplug (on) + Passive Headset

Table 2: MIRE experimental procedure for one subject run

The MIRE experimentation involved assessing the attenuation of all four hearing protectors worn singly and in combination; these devices are listed in Table 1. The full list of combinations tested is given in Table 2 and constitutes one complete set of measurements for a given subject. This set of measurements is referred to as a ‘subject run’. The first four measurements in Table 2 were for calibration and setup of the reverberation chamber and subjects were only present from measurements 5 to 19. One subject run took, on average, four hours to complete. Subjects were allowed breaks from the testing but care was taken not to affect the consistency of the fit of the hearing protectors. For each hearing protector fit, subjects were encouraged to attain the best fit possible and were allowed to alter the fit whilst in the 80dB(A) noise field. This allowed the best possible attenuation to be attained, which is desirable for achieving the levels of attenuation necessary to investigate bone conducted noise.

Microphones were positioned along the air conductive sound transmission path and the positioning of the microphones during the experimentation is shown in Figure 1. The first pair of microphones were used to measure the attenuation of the earshell; microphone 1 was fitted to the outside of the headset, thereby measuring the unoccluded sound field, and microphone 2 was inside the earshell, allowing occluded measurement at this point. The second pair of microphones were fitted in the personally moulded earplugs and allowed measurement of the attenuation of the earplugs themselves and of the total attenuation afforded by the double protection systems. These two were the probe and sense microphones. The probe microphones were fitted to both passive and ANR earplugs, but the since the sense microphone was the microphone of the ANR system it was only present in the ANR earplugs. The output of the microphones was analysed on two Brüel & Kjær (B&K) 2133 third octave band analysers.

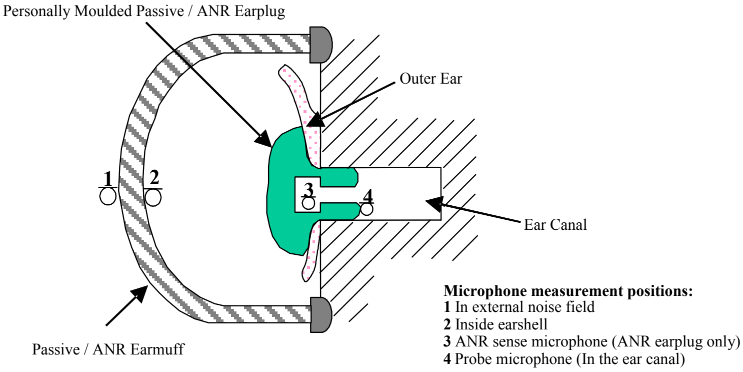

Figure 1: Microphone positions for the MIRE experiment

Measurements were made at the five noise levels, from 80dB(A) to 120dB(A) in 10dB(A) steps. In addition to the five noise levels, the noise floor of the microphones for each condition was also measured. The noise floor is the noise level measured at the microphones without any noise field present and includes the electrical response of the system. To get valid noise level readings from the microphones it is important that the noise level is 10dB higher than the noise floor of that microphone.

The MIRE test standard fully specifies the case of measuring circum-aural hearing protectors, however a method for measurement of MIRE for earplugs is not yet defined. Ideally, a probe microphone would be fitted in the ear canal for both the unoccluded and occluded case, but there are then problems fitting the earplug properly with a microphone and associated cables already in the ear canal. It is for this reason that personally moulded earplugs with probe microphones fitted were used to measure the sound pressure level in the ear canal. In order to obtain the attenuation, this still required the measurement of the unoccluded sound pressure level. The best measurement of the unoccluded sound field would be to remove the sense and probe microphones from the earplugs and locate them at their respective positions at the entrance to the subject's ear canal and within it. This was not practical as it would have required the destruction of all of the earplugs. Therefore, two techniques were adopted, the first involved placing the earplug microphones at the end of a metal tube (dimensions length: 0.03m, inside diameter: 0.007m) and measuring the SPL at the microphones for all 5 noise fields, measurements 03 and 05 from Table 2, for the passive earplug and ANR earplug respectively. This simulated the effect of having the microphones in an open ear canal, as these are the approximate dimensions of an average human ear canal. The second technique ignored the effect of the ear canal resonance and measured the diffuse sound field directly, by simply suspending the earplugs in the diffuse noise field, measurements 02 and 04 from Table 2, for the passive and ANR earplug.

2.2 REAT Experimental Procedure

The combinations of earplugs and headsets that were tested using the REAT method are given in Table 3, and this is a subset of the combinations used with the MIRE procedure. The reasons for this were firstly that the MIRE experimentation had highlighted some key areas of interest, in particular that the double protection systems were reaching the bone conduction limits at frequencies over 2kHz. Secondly, that REAT cannot be used with ANR systems when they are in their active mode of operation, because of the masking effect of the residual ANR noise. Therefore, no ANR 'on' conditions were tested, apart from when the ANR headset was worn over earplugs. Finally REAT depends heavily on the subject's ability to concentrate, hence the number of systems that an individual subject can reliably test in one sitting is limited. Subjects were required to complete the testing without removing their earplugs in order for the same 'fit' to be used for measurements when the headset was changed or removed.

REAT Measurement No.	Measurement Condition	Equivalent MIRE Measurement No.
1	Unoccluded	00
2	Passive Earplug	06
3	Passive Earplug + Passive Headset	07
4	ANR Headset (off)	10
5	ANR Earplug (off)	12
6	ANR Earplug (off) + ANR Headset (off)	14
7	ANR Earplug (off) + ANR Headset (on)	15
8	ANR Earplug (off) + Passive Headset	18

Table 3: REAT experimental procedure for one subject run

The goal was to identify whether bone conduction limits were being reached and, as mentioned above, the previously collected MIRE data indicated that bone conduction limits were being attained above 2kHz, but not at lower frequencies. Therefore, the REAT measurement was made at all the 1/3 octave band frequencies in the range 2kHz to 8kHz and at the standard REAT frequencies (125Hz, 250Hz, 500Hz, 1kHz, 2kHz, 3.15kHz, 4kHz, 6.3kHz and 8kHz). An additional measurement was also made at the 63Hz band. This enabled the region of bone conduction to be investigated in greater detail than the standard REAT method would normally allow.

The REAT method employed 1/3 octave band-limited white noise for the stimulus signal. The experiment was carried out in the reverberation chamber, where the suitability of the room and amplifier/speaker system has been subjected to thorough inspection to make sure it meets the requirements of the ANSI REAT specification.

3.0 RESULTS AND DISCUSSION

The companion paper [14], compares in more detail the review of the measurement techniques used. For the results presented here, all the MIRE earplug / double protection attenuation data has been attained from the probe microphone using the unoccluded freefield attenuation calculation, i.e. without the ear canal simulator. However, it has to be noted, that this will under estimate the MIRE measured attenuation, i.e. attenuation of the sound pressure level in the ear canal. The underestimate will be most noticeable around 2kHz – 3kHz bands, because the unoccluded measurement in the freefield does not measure the open ear canal resonance and the ear canal resonance shifts from around 2.7kHz to around 5.5kHz when the ear canal is occluded [15].

The REAT data presented is mean data for 10 subjects. During the MIRE experimentation the attenuation was shown to be linear over all the noise levels. Hence the MIRE earshell data is the mean over 100 measurements, 10 subjects, left/right ears, 5 noise levels. The earplug and double protection data was the mean over 80 measurements, as it was found that at the 80dB(A) noise level the occluded SPL at the earplug microphones was under the noise floor.

3.1 Single Protection

The mean MIRE attenuation measurements for the single hearing protector devices used during the trial are shown in Figure 2, where the Zwislocki [3] and Berger 1983 [4] BC limits have also been included to provide a comparison. Figure 2a) shows the attenuation for the two headsets used, with the ANR headset showing performance with both ANR on and off. Fitting the ANR system to the Peltor Optime III has reduced the passive performance of the headset. The ANR recoups this "lost" attenuation and over the frequency range 80Hz to 630Hz the attenuation out performs the unmodified headset. The ANR headset is only a prototype device and with more development in fitting the ANR system it is conceivable that the passive attenuation can be brought to match that of the unmodified device. These devices worn singly only approach the Berger bone conduction limit protection around 2kHz.

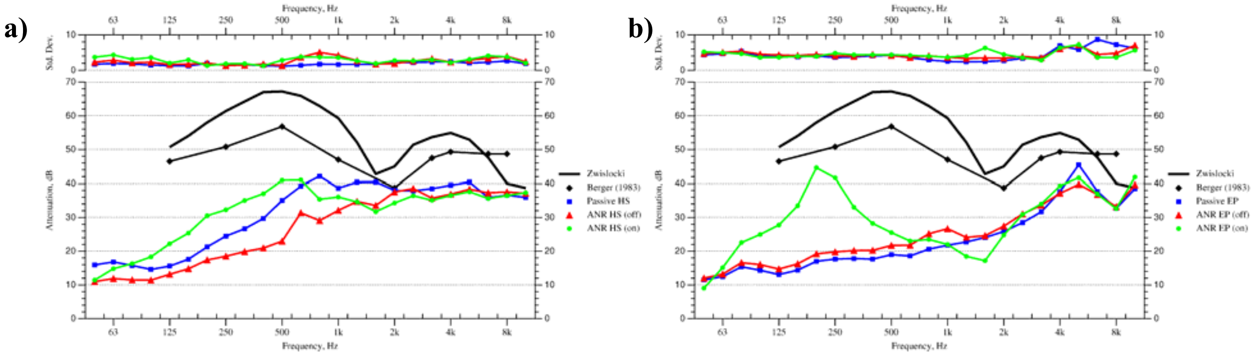

Figure 2: Mean and std. dev. of the attenuations (MIRE data) for the hearing protectors worn singly a) headsets b) earplugs

Figure 2b) shows the individual attenuations for the earplugs. The passive performance of the two earplug types is comparable and, in general, the ANR earplug has better attenuation except in the 1/3 octave band centred at 5kHz. It should be noted that the earplugs were prototypes and specifically designed for the fitting of an ANR system. The passive performance has not been optimised and provides a lower passive attenuation performance than conventional earplugs. The ANR performance provides an increase in attenuation at the low frequencies, with a maximum attenuation increase of 27dB in the 1/3 octave band centred at 200Hz. This brings the attenuation close to the Berger 1983 BC limit for this 1/3 octave band. Figure 2b) shows that the ANR earplug produces noise enhancement in the range of 800Hz to 2kHz (i.e. attenuation performance is worse than when the ANR is switched off). This effect is characteristic of ANR systems and due to a trade off between the levels of active performance at the lower frequencies and the bandwidth of performance. It can be seen that the same enhancement effect, to a lesser degree, is shown by the ANR headset (Figure 2a).

3.2 ANR and Double Protection

As already stated, prior research has indicated that double protection is not a purely additive process. At the higher frequencies this limitation may be attributed to bone conduction limits being reached. However at lower frequencies it has been conjectured that there is some mechanical coupling between the earplug and earshell that limits the performance. The effect of the ANR headset worn over an earplug was considered by Berger et al. [7], where it was found that there was a statistical increase in attenuation in the 125Hz frequency band with the ANR headset switched on. Although, Berger did comment that the relative effect of the 3dB increase on the overall attenuation is negligible. Figure 3 shows the MIRE measured mean attenuation for the ANR headset switched on and switched off worn over the passive earplug and the ANR earplug turned off. When worn over the passive earplug the difference in attenuation with ANR on and off is negligible and a t-test showed there to be no statistical significance ($p < 0.05$) in the difference between the attenuations. When worn over the ANR earplug there is a noticeable increase in attenuation between ANR on and off in the range 80 to 160 Hz, which was found to be statistically significant ($p < 0.05$). However at 125Hz there is only a 3dB increase in the double protection as opposed to an increase of 11dB for the headset worn singly. This minimal advantage provided by the headset ANR system is also shown in the REAT measurements, see figure 5b). At the higher frequencies (above 2kHz) there is no change in overall performance between ANR on and off for the device worn alone, therefore no change at these frequencies is not entirely unexpected. At the lower frequencies, particularly 250Hz and 500Hz, the additional active attenuation of the headset is not passed onto the overall double protection. At these frequencies the attenuation levels fall short of the bone conduction limits previously identified and therefore the limitation cannot be due to bone conduction limits being reached. Zwislocki [3] and Berger [4] also indicated this effect for headsets with different attenuating properties not changing the overall attenuation when headsets were worn over earplugs.

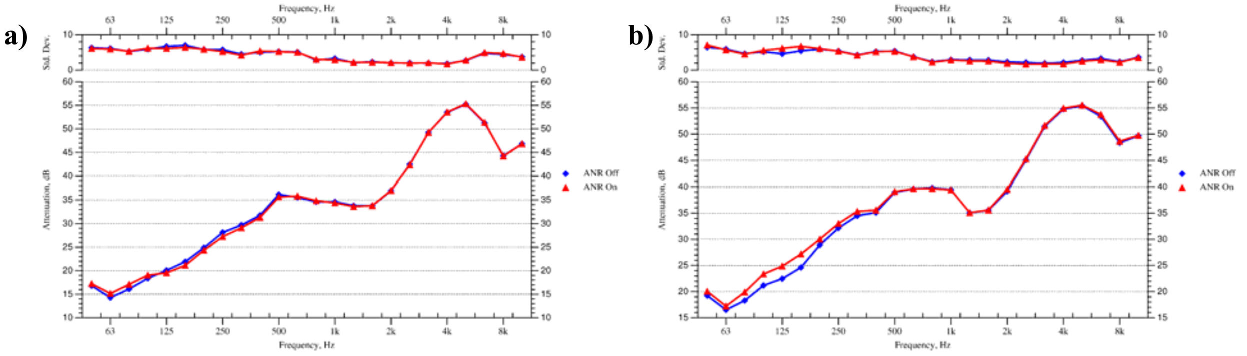

Figure 3: Mean and std. dev. of the attenuations (MIRE data) for ANR headset (on/off) worn in combination with a) Passive earplug and b) ANR earplug (off)

Earplug attenuation has been found to have a direct impact on the overall attenuation of double protection systems. The ANR of the earplug (see Figure 4a) evidently has an effect on the sound pressure level in the ear canal. Below 2kHz, when the ear canal is occluded at its entrance (i.e. standard fitted earplugs), the dominant BC pathway is via the SPL in the ear canal. Therefore at these frequencies for standard fit earplugs, the MIRE measured attenuation will give an accurate prediction of the attenuation seen by the user. Hence, the active attenuation of ANR earplugs can give a significant increase of attenuation when used in a double protection system. Figure 4b compares the attenuation data between the passive earplug and ANR earplug turned off when both were worn in conjunction with the passive headset. The results are similar to Figure 4a) in that the change in earplug attenuation changes the overall double protection attenuation.

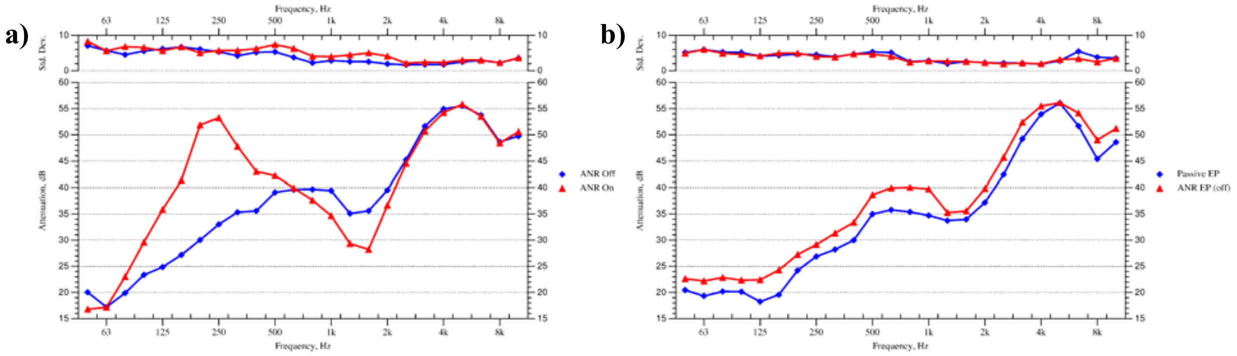

Figure 4: Mean and std. dev. of the attenuations (MIRE data) for a) ANR earplug (on/off) worn in combination with the ANR headset (on) and b) Passive earplug or ANR earplug (off) worn in combination with the passive headset

Figure 5a) shows the effect of changing the earplug attenuation when worn under a headset when using the REAT technique. At frequencies above 2kHz there is strong correspondence between the two curves, and as we are considering REAT data it is likely that this is due to bone conduction limits, noting also that this is not the case for the MIRE data in Figure 4b). However, below 2kHz there is marked effect on the attenuation and here the attenuation falls short of the bone conduction limits. This indicates that for double protection it is the attenuation of the earplug that is most important in defining the overall attenuation.

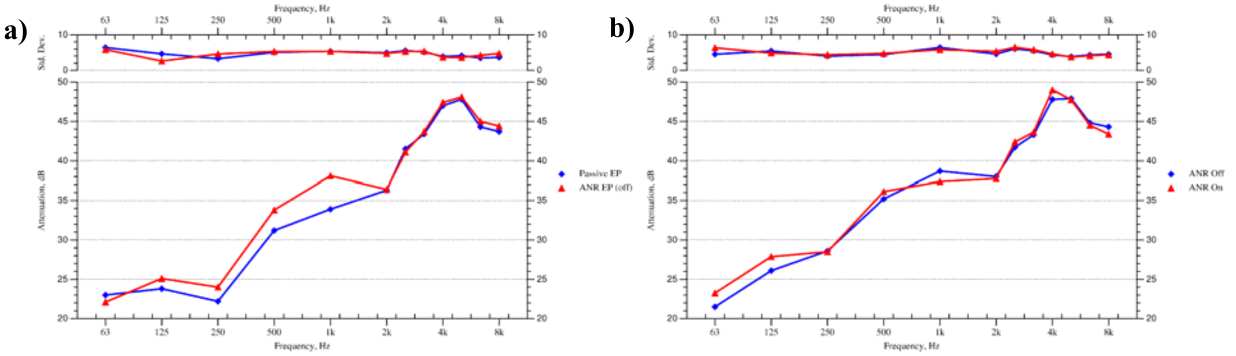

Figure 5: Mean and std. dev. of the attenuations (REAT data) for a) Passive earplug or ANR earplug (off) worn in combination with the passive headset and b) ANR headset (on/off) worn in combination with ANR earplug (off)

3.3 Earshell Attenuation

During the MIRE experimentation, the sound pressure level was measured under the earshells, when the headset was worn over the earplugs as well as when worn singly (see figure 2a). This was to facilitate further investigation into why the addition of double protection is not purely additive. Figure 6a) shows the mean attenuation provided by the passive headset when worn alone and with all combinations of earplug. Figure 6b) shows the mean attenuation provided by the ANR headset (on) when worn alone and with all combinations of earplug.

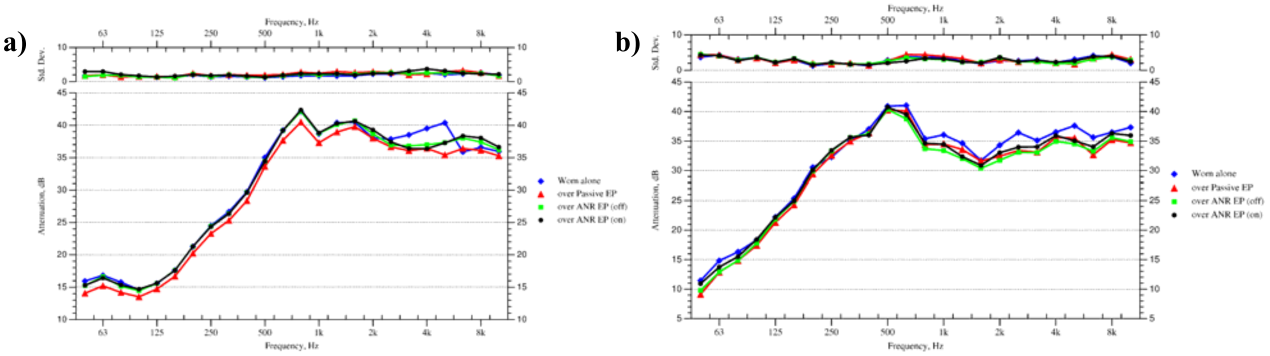

Figure 6: Individual attenuation of hearing protectors when worn as double protection, for a) passive headset mean attenuation over all combinations of earplug and b) ANR headset (on) mean attenuation over all combinations of earplug

The attenuation under both earshells is consistent apart from some small discrepancies, which could conceivably be put down to earshell fit, the position of the microphone within the ear shell and the reduced volume due to the earplugs being present. These graphs indicate that not only is the passive attenuation consistent but the active attenuation of the ANR headset is also working consistently when worn in combination with the earplugs. Exactly the same results were found for the ANR headset with the ANR turned off. This means there is no degradation of earshell attenuation, implying that there is mechanical coupling between the earplug and earshell that reduces the overall attenuation.

3.4 Bone Conduction Limits

Figure 7 compares the MIRE and REAT measured mean attenuation. Figure 7a) shows the attenuation for ANR earplug turned off worn in conjunction with the ANR headset turned on and Figure 7b), the passive earplug worn in conjunction with the passive headset. The dominant bone conduction pathway above 2kHz is via the middle ear and inner ear, hence the sound pressure level in the ear canal does not factor in predicting the attenuation once the BC limit has been reached. As discussed in the companion paper [14], this implies that MIRE will predict higher attenuations, when at BC limits, than occur in reality above 2kHz. REAT on the other hand includes the inner and middle ear BC components and so measures the BC limited attenuation. In Figure 7a) and b) the MIRE data over predicts the attenuation above 3.15kHz, and implies that at these frequencies the BC limit has indeed been reached. Also, as mentioned, the MIRE technique used for calculating earplug attenuation (i.e. freefield – unoccluded) will tend to under estimate the attenuation, particularly in the 2-3 kHz bands. Implying that the MIRE measured attenuation would be higher in the 2kHz and 2.5kHz bands, indicating bone conduction being reached at these frequencies also.

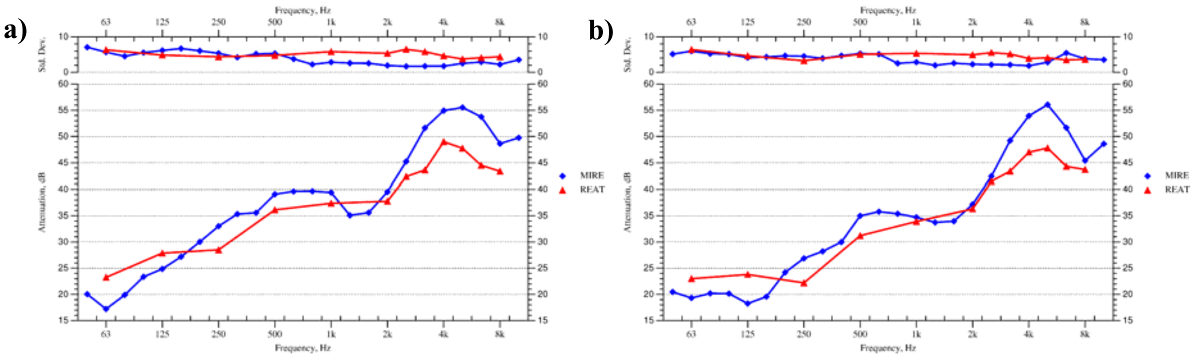

Figure 7: Comparing MIRE and REAT for double protection systems, for a) ANR earplug (off) worn in combination with the ANR headset (on) and b) Passive earplug worn in combination with the passive headset

Figure 8 shows the BC limits that can be inferred from this study. The curves in Figure 8a) show the attenuation of the ANR Earplug turned off when worn under the ANR headset turned on. This is considered the "passive" BC limit as there is no direct ANR effect on the attenuation. The REAT curve is simply the REAT attained attenuation. The second ("hybrid") curve is a combination, as suggested in [14], of the REAT measured data above 2kHz and the MIRE measured data below 2kHz. As with Figure 2 the Zwislocki and Berger 1983 bone conduction limits are included for comparison. It is clear that the there is a shortfall of attenuation at the low frequencies. However, in order to attain the levels of attenuation at low frequencies both Zwislocki and Berger used deeply inserted earplugs (into the bony part of the ear canal), which circumvents the BC pathway of the soft tissue of the ear canals oscillating. It is unsurprising that the earplugs in the current study, with a poorer passive performance and not deeply inserted, don't reach the Berger and Zwislocki BC limits.

At the frequencies above 2kHz the attenuation is comparable to the previous BC data either close to the Berger 1983 curve or Zwislocki's curve, where at 3.15kHz there is 5dB drop from the Berger 1983 curve. This implies that, further to the above discussion the work has reach bone conduction limits above 2kHz.

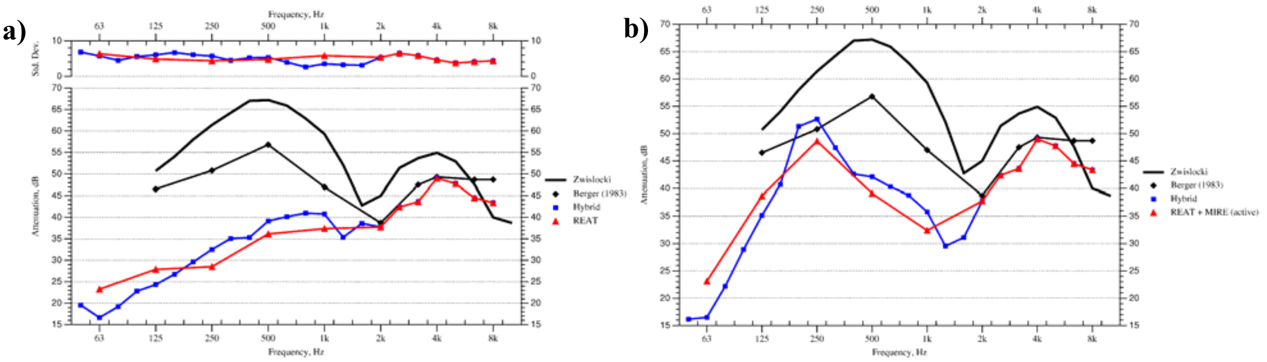

Figure 8: Predicted bone conduction limits for the current study, for a) "passive" BC and b) "active" BC

Figure 8b) shows the "active" BC limit that can be inferred from the current work. The "hybrid" curve is constructed from the mean REAT attenuation of the ANR Earplug (off) under the ANR Headset (on) above 2kHz and, below 2kHz, from the mean MIRE attenuation of the ANR Earplug (on) under the ANR Headset (on). The REAT plus MIRE (active) curve, is the same as the "hybrid" curve above 2kHz and, below 2kHz, it is the REAT attenuation with ANR Earplug (off) under the ANR Headset (on) plus the MIRE measured active attenuation only for the ANR earplug (on). The justification of not including the ANR earplug effect over 2kHz is that as the ANR only effects the SPL in the ear canal and as this is not part of the dominant BC pathway it will give a negligible effect on the overall attenuation. However the importance of this curve is the attenuation given at the lower frequencies. This shows that ANR fitted in an earplug allows a shallow fit of earplug (in a double protection system) to reach the bone conduction limits achieved by deeply inserted plugs (used in a double protection system), even if only over a limited range of frequencies. If the ANR earplugs were designed to provide better passive attenuation, the active attenuation seen here could provide similar levels of low frequency attenuation as deeply inserted earplugs.

5.0 CONCLUSION

The work has shown that the active attenuation of an ANR headset appears to offer little advantage when used over earplugs in a double protection system. However ANR earplugs have been shown to increase the low frequency attenuation when worn in combination with either active or passive headsets. Even with the poor passive performance of the moulded earplugs used in this study the active attenuation of ANR earplugs used in a double protection system has reached BC limits attained by deeply inserted plugs. This indicates that standard fit ANR earplugs are a viable alternative to deep inserted earplugs, as they are more practical and easier to fit.

The work has also shown that although the attenuation afforded by the double protection is not a simple additive process, the headset suffers no degradation of performance when worn over earplugs. This implies that there is likely to be some mechanical coupling between the headset and earplug that reduces the overall attenuation attained.

REFERENCES

[1] A. Behar. Sound attenuation from combinations of earplugs and earmuffs. *Applied Acoustics*, 32(2):149–158, 1991.

[2] S. M. Abel, N. M. Armstrong. The combined sound attenuation of earplugs and earmuffs. *Applied Acoustics*, 36:19-30, 1992.

[3] J. Zwislocki. In search of the bone-conduction threshold in a free sound field. *Journal of the Acoustical Society of America*, 29(7):795–804, July 1957.

[4] E. H. Berger. Laboratory attenuation of earmuffs and earplugs both singly and in combination. *American Industrial Hygiene Association Journal*, 44(5):321–329, 1983.

[5] C. W. Nixon and H. E. Gierke. Experiments on the bone-conduction threshold in a free sound field. *Journal of the Acoustical Society of America*, 31(8):1121–1125, August 1959.

[6] A. Behar and H. Kunov. Insertion loss from using double protection. *Applied Acoustics*, 57(4):375–385, August 1999.

[7] E. H. Berger, R. W. Kieper, and D. Gauger. Hearing protection: Surpassing the limits to attenuation imposed by bone-conduction pathways. *Journal of the Acoustical Society of America*, 114(4):1955–1967, 2003.

[8] J. Tonndorf. Bone Conduction in *Foundations of Modern Auditory Theory Vol II*. Academic Press London, 1972.

[9] S. M. Kanna, J. Tonndorf, and J. E. Queller. Mechanical parameters of hearing by bone conduction. *Journal of the Acoustical Society of America*, 60(1):139, July 1976.

[10] S. Stenfelt, T. Wild, N. Hato, and R. L. Goode. Factors contributing to bone conduction: the outer ear. *Journal of the Acoustical Society of America*, 113(2):902–913, February 2003.

[11] E. A. Goodfellow. A prototype active noise reduction in-ear hearing protector. *Applied Acoustics*, 42: 299-312, 1994.

[12] ANSI S12.42-1995: Microphone-in-Real-Ear and Acoustic Test Fixture methods for the measurement of insertion loss of circumaural hearing protection devices. *American National Standard*, 1995.

[13] ANSI S12.6-1997: Methods for the measuring the Real-Ear Attenuation of hearing protectors. *American National Standard*, 1997.

[14] Susan E. Mercy, Christopher Tubb and Soo H. James. Experimentation to address appropriate test techniques for measuring the attenuation provided by double ANR Hearing Protectors, *In Proceedings of the HFM Symposium on New Directions for Improving Audio Effectiveness,* April 2005.

[15] S. Stenfelt, N. Hato, and R. L. Goode. Factors contributing to bone conduction: the middle ear. *Journal of the Acoustical Society of America*, 111(2):947–959, February 2002.