Exposure to very high noise levels and the effect of double hearing protection

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ABSTRACT

The risk of noise induced hearing loss increases for operators working in extreme noise environments. Although the use of earplugs and earmuffs as 'double protection' may be the obvious solution, the attenuation of a double hearing protection system is not simply the addition of the individual component attenuations. The choice of devices and the implementation can also result in a number of outcomes: the integration of communications wiring may cause acoustic leaks, the wearer may be over-protected and feel isolated and the interaction of earplug and earmuff may cause discomfort and discourage take-up. A variety of hearing protection devices currently on the market have been examined with a view to their use in a double protection system. Wireless technologies enable the provision of a communications signal to an earplug worn beneath an earmuff without compromising the attenuation benefit of the double protection system. Adaptive systems, such as the 'tactical' communications earplugs and techniques such as adaptive digital active noise reduction, provide a method of tailoring levels of hearing protection to the noise environment. Using military operators as an example user group the application of a range of earplug devices as part of a double protection system have been considered and illustrations have been provided of their relative abilities to meet the users' protection requirements.

INTRODUCTION

The noise encountered by many military personnel can be extremely high due to the nature of the vehicles and equipment they operate and the presence of additional noise sources such as communications and audio warning systems. The noise to which aircrew are exposed can reach levels of around 120 dBA and with the introduction of the next generation of Combat Aircraft the exposure of ground and deck crew is predicted to reach 150 dBA (Bjorn 2008). Similarly for land base operators: the crew of heavy tanks and armoured fighting vehicles may well be exposed to levels between 110 dBA and 120 dBA and the weapons fired by the infantry can produce peak pressure levels of some 190 dB (Paakkonen & Lehtomaki 2005; Buck & Hamery 2010).

In these environments, the noise attenuation provided by earmuffs or earplugs when worn singly can be inadequate to bring the daily personal noise dose down to below the legislative limits. The simplest solution would appear to be to recommend the wearing of earplugs underneath an earmuff. However, this does not provide the levels of attenuation that might be expected if the attenuation values for each device when worn singly are simply added together. There are other issues that also need to be taken into account when wearing double hearing protection systems, such as the provision of communications and the ability to hear external warnings.

DOUBLE HEARING PROTECTION

Attenuation and bone conducted noise

The most common hearing protection devices aim to reduce the level of sound transmitted along the auditory canal to the inner ear. However, noise can reach the cochlea by three other routes collectively known as bone conducted noise (Tonndorf 1972). Noise that impinges upon the body may be transmitted by the flesh and bone of the head, causing the cartilage of the ear canal to vibrate and to generate additional sound pressure levels in the ear canal in front of the ear drum. This is known as the 'occlusion effect', which dominates at frequencies below 2 kHz (Khanna et al. 1976; Stenfelt et al. 2003). Noise may also be transmitted to the cochlea directly by the bones of the skull and by the fluid contained within the inner ear (including the semi-circular canals). These last two transmission routes are difficult to separate and dominate at frequencies above 2 kHz. When the auditory canal pathway is attenuated sufficiently, these bone conduction pathways to the cochlea become increasingly important.

The highest levels of attenuation achieved by a double hearing protection system that have been reported were obtained by Berger (1983). He inserted E.A.R.® 'Classic'™ foam earplugs as deeply into the ear canal as possible (100 % insertion depth) and then placed earmuffs over the ears. Decreasing the volume of the earshells or increasing the mass of the earmuffs did not affect the level of attenuation achieved in this double protection system. This, together with measurements using different earplug insertion depths, appeared to show that the earplug forms the driver in the level of attenuation possible in a double protection system.

In a previous experiment, the authors investigated the role of the earmuff in double hearing protection. A miniature microphone was clipped inside an Active Noise Reduction (ANR) earmuff which was worn over a custom moulded earplug that incorporated a microphone at the tip. The Sound Pressure level (SPL) could therefore be measured simultaneously beneath the earmuff and in the wearer's ear canal (Tubb et al. 2005). The results showed that the SPL in the ear canal was unchanged whether the earmuff was left in its passive mode or whether the ANR was activated. The SPL measured under the earmuff showed that the ANR system operated correctly, but the additional attenuation provided by the ANR system was apparently 'lost' when measured in the earcanal, on the occluded side of the earplug.

The reason for the apparent loss in attenuation of the earmuff when worn in a double protection system has yet to be established and is likely to be due to a complex interaction of the earmuff with both the earplug and the wearer's head. At frequencies above 2 kHz, the auditory canal is sufficiently attenuated that higher levels of attenuation can only be achieved by shielding the head and torso. At frequencies below 2 kHz, the occlusion effect must be overcome. Although the occlusion effect can be overcome by inserting foam earplugs sufficiently deep to prevent movement of the cartilaginous walls of the ear canal, the same level of protection is unlikely to be achieved in the field with real users due to the difficulty of fitting these types of earplug sufficiently deep. There may also be effects due to the interaction of the earmuff and earplug either directly, due to contact between the surfaces of the two devices, or indirectly, due to the connection of the two devices by the air under the earmuff or by flanking pathways including the tissues of the head and ear.

Communications

The noise from the environment is not the only source of noise reaching the ear of military operators; they may also receive a communications (comms) signal via the loudspeaker in the earmuff. The wearing of a passive earplug beneath the earmuff will result in the attenuation of the comms signal along with the environmental noise. The wearing of a comms earplug underneath the earmuff enables a reduction in the environmental noise whilst retaining a clear comms signal. This has an additional benefit in that this reduction in the noise allows the comms signal itself to be reduced to maintain the same signal to noise ratio, thereby reducing the total noise at the ear.

Most comms earplugs currently available rely on a cable to provide the signal to the loudspeaker enclosed within the body of the earplug. This cable must be located carefully to minimise the level of acoustic leak that occurs if the earseal is broken.

Isolation

It is important when choosing any hearing protection system that it meets the requirements of the end user and that the hearing protection with the highest levels of attenuation is not chosen simply in order to meet the legislative limits. In the guidance to the Control of Noise at Work Regulations (CNAWR):2005 (HSE 2005), a level of 70 dBA is set as the lower limit on noise at the ear, to help prevent over-protection and the associated feelings of isolation. Excessively high levels of hearing protection (over and above that required to meet the noise exposure limits) reduce the reliable detection of important audio cues taken from the working environment and may constitute a safety risk or limit operational effectiveness.

HEARING PROTECTION DEVICES

A review of commercially available hearing protection devices and some near future technologies was made to establish the best performing devices and those with the best attributes for use in a double hearing protection system, bearing in mind the issues mentioned in the previous section.

Earmuffs and earplugs

There are three main types of earmuff currently on the market: passive, electronically enhanced and pass-through. Electronically enhanced earmuffs can include communications earmuffs and earmuffs incorporating ANR systems. Pass-through systems include 'shooters' earmuffs and tactical earmuffs designed to transmit sound from the environment through the earmuff to the ear.

Earplugs are also available in passive, electronically enhanced and fitted with filters. Over the last ten years or so, custom moulded earplugs have become more widely available. A comparison of personally moulded earplugs including one 'self-moulded' earplug by the UK's Health and Safety Laboratories found that the attenuation performance of the earplugs can be significantly lower than the supplied manufacturer's data (Shanks & Patel 2009).

Earplugs with acoustic filters are available that aim to provide a more selectable level of hearing protection compared to a solid passive earplug. These include 'musicians' earplugs in which the filter aims to produce attenuation with a flat frequency response, although filters with other spectral characteristics are also available. A number of earplugs are now available that incorporate ANR and tactical earplugs that have primarily been developed for the military are becoming more prevalent.

ASSESSMENT OF EARPLUGS AND DOUBLE HEARING PROTECTION

The wide range and variety of hearing protection devices on the market were examined for their usefulness in extreme high noise environments and three candidate earplug technologies were down-selected for test as part of a double protection system. The main factors considered in the selection process were: the levels of noise attenuation; provision of a communications signal and over-protection.

A communications earplug offers the best approach to attenuating the ambient noise whilst retaining high speech intelligibility. Whilst the wireless technologies described in the previous section are novel, they are not currently commercially available and so wired comms earplugs were used in the assessment. Three communications earplugs were down-selected for test: the Mini-CEP from Communications & Ear Protection Inc., the 'Omara' earplug from Amplifon and a tactical earplug example.

- The Mini-CEP can be either personally moulded or provided with a foam tip for generic fit. The device consists of a transducer housing and a foam/moulded canal tip that provides passive attenuation. The canal tip has a central hollow 'core' that allows the comms signal to pass into the ear canal without being attenuated.
- The Omara earplug is a silicone custom-moulded device. It can be fitted with one of a range of interchangeable filters that use the physics of small cavities to alter the attenuation of the earplug. The earplug provides a comms signal direct into the earcanal.
- A tactical earplug that can be either personally moulded or fitted with a foam tip for generic fit. The device allows the electronic pass through of ambient sound and direct speech to the ear in low noise environments. It provides comms directly into the earcanal and uses an in-ear microphone for the transmission of speech. The device also provides protection against high level impulse noise.

In order to understand the comparative performance of these particular devices and the benefits they may provide for military operators, measurements of their attenuation performance were made using the Real Ear Attenuation at Threshold (REAT) technique (ANSI S12.6, 1997). The attenuation provided by the Mini-CEP and the Omara earplugs was measured when used in combination with a UK flight helmet.

However, as the tactical earplugs are designed to amplify low levels of sound, the attenuation of the selected device could not be measured using the standard REAT technique and, instead, it's attenuation as a function of the pass-through functionality was measured using a Brüel & Kjær (B&K) Head and Torso Simulator (HATS).

The assessment of these devices formed part of a larger research program and only a small number of subjects were used at this stage to provide an indication of comparative performance. Full measurements should be undertaken using a recognized test-house to the relevant standard if the solutions are to be taken forward.

RESULTS

Attenuation of Mini-CEP and helmet

The mean attenuation and associated standard deviations measured for the helmet and the Mini-CEP used in combination are shown in Figure 1. Measurements were made for 8 subjects at the frequencies specified in the REAT standard. High levels of attenuation were exhibited right across the frequency range and, hence, due consideration must be given in any application of this double protection system to ensure it does not constitute over-protection.

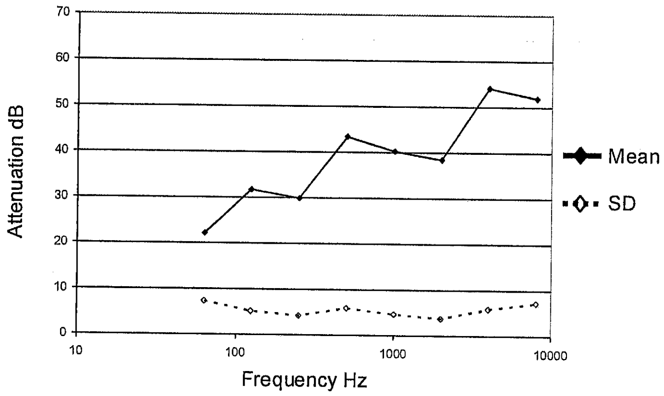

Figure 1: Mean attenuation and associated standard deviations of helmet plus Mini-CEP used as a double hearing protection system (8 subjects)

Attenuation of Omara earplug and helmet

The mean attenuation and associated standard deviations for the Omara earplug fitted with a range of filters providing different levels of attenuation (the LD10, LD14, LD18, LD22 and LD24 filters) are shown in Figure 2 (a). Measurements were made on 4 subjects using the REAT technique over an extended range of 24 frequency bands. The effect of the different filters can be seen by the spread in the levels of attenuation at frequencies below 630 Hz.

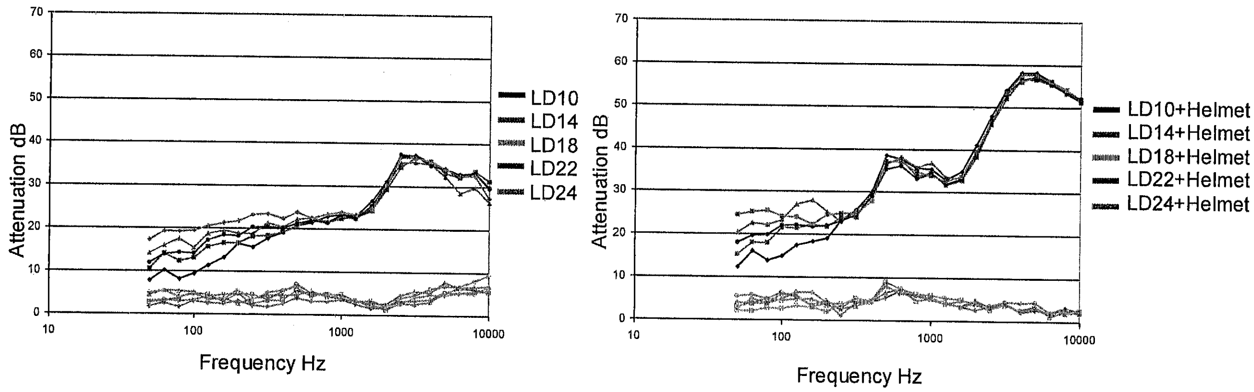

Figure 2: Mean attenuation and associated standard deviations of the helmet plus Omara earplug with different filters used as a double hearing protection system (4 subjects)

When the helmet was worn over the Omara earplug, the attenuation showed a much reduced range of variation due to the different filters, as shown in Figure 2 (b). The variation in attenuation afforded by this double protection system occurred at frequencies below 250 Hz. The reduction in the range of frequencies over which variation in attenuation was exhibited is probably due to complex interactions between the helmet, earplug and the wearer's head. Whilst it is not currently clear what the exact mechanisms are, the limited range of variability must be taken into account in any application of this double protection system to ensure it provides an effective solution.

Attenuation of the Tactical Earplug

The operation of the tactical earplug was measured when fitted to the B&K HATS in Pink noise generated at five different Overall Sound Pressure Levels (OASPLs). The dynamic pass-through system of the earplug was set to off, to provide the passive performance of the earplug, and to its minimum, mid and maximum settings. For each condition the SPL was measured at the microphones within the ears of the HATS. The results are shown in Figure 3.

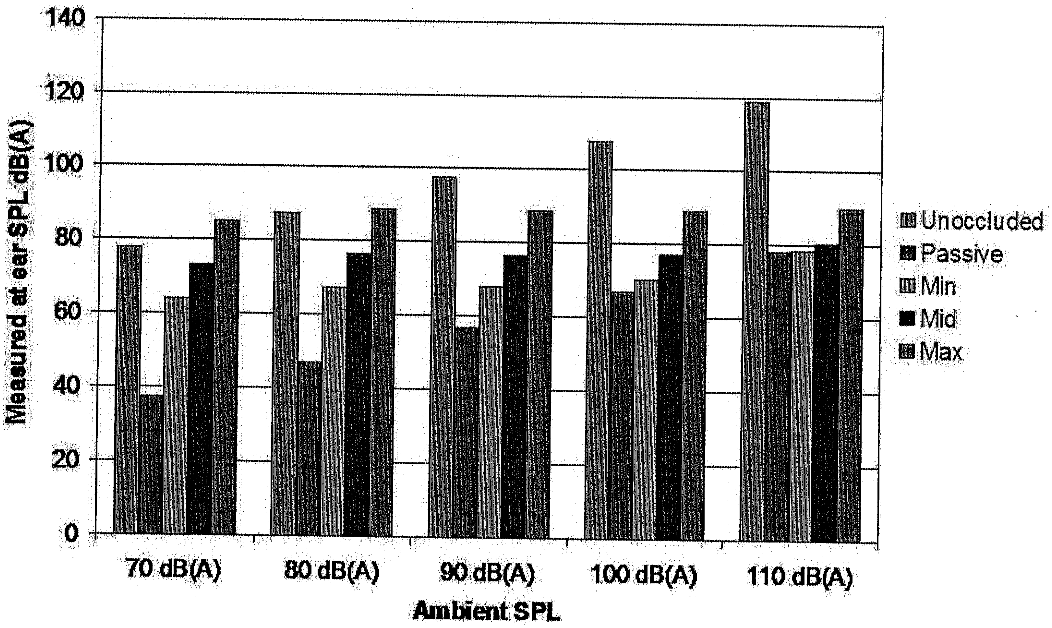

Figure 3: Overall A-weighted SPL measured on the B&K HATS for the tactical earplug with different settings of the dynamic pass-through system in increasing levels of Pink noise

The figure shows that as the ambient noise field (unoccluded) was increased in level, the OASPL on the occluded side of the earplug when the dynamic pass-through system was switched off increased in an associated fashion, since the passive attenuation of the earplug was constant. In noise fields up to 100 dBA varying the level of pass-through provided good levels of variation in noise reaching the ear (i.e. good variable attenuation). However, in the highest ambient noise (110 dBA), the OASPL in the earcanal with the pass-through system at the minimum and mid-positions was similar to that of the earplug in its passive state, since the electronics limit the absolute levels of noise reaching the ear to a safe level.

Whilst the tactical earplug appears to offer a means of varying the level of protection afforded it is not possible with current measurement techniques to calibrate the pass-through to provide absolute levels of attenuation and, hence, to be of practical use in a double protection system at this time.

EFFECT OF DOUBLE HEARING PROTECTION ON NOISE AT EAR

In order to illustrate the impact of the choice of earplug device used in a double protection system the helmet+Mini-CEP and helmet+Omara figures were applied to noise dose data collected for military aircrew.

There are a number of aircraft for which the attenuation provided by the standard aircrew helmet when worn alone is insufficient to meet the legislative requirements of CNAWR. The daily personal noise exposure was calculated for a number of these aircraft environments and the shortfall in the levels of attenuation required to meet CNAWR was determined and is shown in column 2 of Table 1. Column 3 of the table provides the attenuation afforded by the helmet+Mini-CEP over and above the attenuation of the helmet itself. The final (4th) column of the table indicates the level of additional protection, over and above that required to meet the regulations. This additional protection was, for the majority of aircraft, quite high and has the potential to mask the wearer's detection of noise and audio cues generated in the immediate environment and may cause feelings of isolation and reduce situational awareness.

Table 1: Calculated attenuation required to meet CNAWR for 12 Aircraft and additional attenuation provided by double protection with the Mini-CEP

Aircraft type	Additional Protection Required	Protection provided by Mini-CEP component	Overprotection/ Shortfall
1	9.0	19.9	10.9
2	8.0	13.8	5.8
3	2.4	22.8	20.4
4	10.2	19.8	9.8
5	8.2	19.8	15.8
6	10.0	19.5	10.5
7	4.0	19.5	6.5
8	9.0	21.9	11.7
9	13.0	22.1	16.9
10	10.2	21.2	10.8
11	5.2	20.5	20.5
12	10.4	21.0	21.0

Further work is needed to understand whether this high level of additional protection provided by the helmet+Mini-CEP constitutes overprotection and poses a safety risk for military aircrew.

The same calculations were performed for the Omara earplug fitted with three different filters when worn as a double hearing protection system. These results are shown in Table 2.

Column 2 provides the additional protection required to meet the CNAWR for the same 12 aircraft as in Table 1. The additional protection afforded by the Omara earplug fitted with the LD24 filter over that afforded by the helmet alone is provided in column 3. The level of over-protection (positive values) or the shortfall in protection (negative values) that this affords is provided in column 4. These calculations are repeated in columns 5 and 6 for the earplug fitted with the LD14 filter and in columns 7 and 8 for the earplug fitted with the LD10 filter. Those cells highlighted in red indicate that the earplug does not provide sufficient attenuation to meet the CNAWR, even when fitted with the most highly attenuating filter. However, it is possible that a solid version of the plug may satisfy the requirements for these aircraft. **Table 2:** Calculated Attenuation Required to meet CNAWR for 12 Aircraft and additional attenuation provided by double protection with the Omara earplug fitted with three different filters.

Table 2: Calculated attenuation required to meet CNAWR for 12 Aircraft and additional attenuation provided by double protection with the Omara earplug fitted with three different filters

Aircraft type	Additional Protection Required	Protection provided by LD24 plug	Over protection /Shortfall LD 24	Protection provided by LD14 plug	Over protection /Shortfall LD 14	Protection provided by LD10 plug	Over protection /Shortfall LD 10
1	9.0	11.5	2.5	9.3	0.3	6.8	-2.2
2	8.0	6.2	-1.8	3.9	-4.1	5.7	-2.3
3	2.4	14.5	12.1	10.7	8.3	7.0	4.6
4	10.2	9.9	-0.3	8.9	-1.3	10.2	0.0
5	8.2	9.9	1.7	8.9	0.7	10.2	2.0
6	10.0	7.6	-2.4	6.4	-3.6	7.1	-2.9
7	4.0	7.6	3.6	6.4	2.4	7.1	3.1
8	9.0	11.0	2.0	9.4	0.4	7.3	-1.7
9	13.0	11.4	-1.6	10.0	-3.0	8.2	-4.8
10	10.2	10.4	0.2	8.6	-1.6	7.1	-3.1
11	5.2	9.5	4.3	8.6	3.4	9.2	4.0
12	10.4	10.2	-0.2	9.2	-1.2	10.3	-0.1

The cells highlighted in yellow indicate that the required levels of additional protection is met for the Omara earplug fitted with that particular filter, when worn with the helmet as part of a double hearing protection system. The filter best suited to meet the needs of a particular aircraft will be dependent on the spectral characteristics of the aircraft cockpit noise and whether dominant tonal components fall below 250Hz. This type of device, therefore, offers the ability to accurately match the attenuation requirements of each individual platform.

CONCLUSIONS

Double hearing protection systems appear to offer the simplest solution to reduce hearing damage risk and enable employers to meet the legislative requirements. However, due to the interaction between the earplug, the earmuff and the head and torso, the attenuation afforded by the double protection system must be considered as a whole and must be measured using human participants.

For military application the choice of earplug and earmuff must be considered carefully to ensure that the level of overall protection afforded is commensurate with operators requirements and the balance between sufficient protection and overprotection is achieved.

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