Proceedings of the Institute of Acoustics

SOME LIMITATIONS IN THE USE OF HEARING PROTECTION?

G.Kerry University of Salford, Salford, M5 4WT, UK
C.Lomax University of Salford, Salford, M5 4WT, UK

1 INTRODUCTION.

The current Noise at Work Regulations (NAWR) [1] requires under regulation 8(2) that "*Every employer shall ensure, so far as is reasonably practicable, that when any of his employees is likely to be exposed to the second action level or above or to the peak action level or above, that employee is provided with suitable personal ear protectors which when properly worn, can reasonably be expected to keep the risk of damage to that employee's hearing to below that arising from exposure to the second action level or, as the case may be, to the peak action level.*" The new EU Physical Agents (noise) directive [2] states in Article 7 para 2 "*When applying the exposure limit values, the determination of the worker's effective exposure shall take account of the attenuation provided by the individual hearing protectors worn by the worker. The exposure action values shall not take account of any such protection*." There is therefore a requirement, both current and future, to assess the performance of hearing protectors for use against all sources of noise when the level of that noise exceeds the action levels or limit levels.

Data for use when assessing the value of wearing particular models of ear muffs are obtained using a technique, which requires judgements to be made at or around the threshold of hearing [3]. Some investigations have been made into alternative methods especially for use in relatively high levels of impulsive noise [4]. Methods are available [5] for the selection of protection for appropriate environments involving both the A-weighted continuous equivalent sound pressure level and the peak sound pressure level. However these methods are approximate and the reliance on data measured under threshold conditions for use at very high levels of noise such as those around and above the peak action level (140dB re 20uPa) has to be questioned. This applies particularly to the use of double protection (muff and plug) which have to be used against extremely high noise levels. Recent standardisation of techniques involving MIRE (microphones in real ear) methodologies [6] has resulted in renewed interest in finding suitable miniature microphones and methods of calibration particularly for use in high levels of noise. It was whilst undertaking some development work in this area that it became apparent that slight bumps and bangs on the muff can apparently generate relatively high noise levels under the cup.

Most ear muffs are lightweight and are designed so that they do not impede head movement. They allow the wearer full freedom of movement in the workplace. There is a tendency for some users to keep the protection in place even when away from the noisy zone or when the noise has been turned off. With the use of hearing defenders or muffs both conventional or helmet mounted it is quite possible to accidentally knock or bump the protectors during use, for instance against scaffolding or a doorway. It also possible, say for verbal communication purposes, to have one or both cups lifted from the head and subsequently released back into position. Other situations that arise which could result in high noise levels under the cup could include rapid movement of the head, such as when in a vehicle (especially off-road) or when running or jumping.

The opportunity was therefore taken to investigate this matter further.

2 INSTRUMENTATION

2.1 Selection of microphone

When checking noise levels against internationally agreed action or limit values, a knowledge of the uncertainties in the measurement is essential. Therefore as far as possible the measurement protocol should adopt recognised procedures and should use equipment that is stable and which is capable of being calibrated and referenced back to international standards. This means that a well-defined calibration path is required. As with any acoustic measurement the key to success lies in the choice of microphone. The requirements for the microphone for these “under the cup” measurements relating to peak action levels can be summarised as follows:

- Capable of measuring peak sound pressure levels in excess of 140dB and preferably 150dB
- Able to be placed at the entrance to the ear canal or in the cup adjacent to the ear canal without significantly affecting the sound field
- Have a very small diameter cable that doesn’t break the seal between muff and head
- Easily calibrated using traceable sources
- Provide reliable repeatable measurements over a broad frequency range

Generally, available precision capacitor microphones will not readily meet all these requirements largely because of the size and nature of their preamplifiers. In particular connections tend to be rigid limiting the positioning of the microphone that should preferably conform to the requirements of BS EN ISO 11904 [4]. The specifications for several miniature microphones were considered and two selected for further evaluation:

1) A Sennheisser MKE 2-4 Gold C with the following nominal characteristics

Directionality – Omni-directional
Frequency response (nominal) – 20Hz to 20kHz
Maximum peak SPL (@1kHz) – 142dB

It was necessary to provide a suitable power supply that would allow operation of the microphone at such high levels.

2) A Knowles CA 2832 with the following characteristics

Directionality – Omni-directional
Frequency response (nominal) – 100Hz – 7kHz
Maximum peak SPL – 144dB

No miniature microphones could be sourced that had a maximum level capability above this level. Therefore to allow checks to be made at higher levels, one pair of ear muffs was adapted to fit a B&K type 4136 microphone fitted directly on to a standard type 2670 pre-amplifier. This entailed drilling a clearance hole in one of the cups and inserting the microphone on its adapter so that it was positioned near the entrance to the ear canal with the protector in place. It was sealed in position through the cup with flexible sealant and the preamplifier resiliently attached to the headband to minimise the effect on the fitting of the cup around the ear and of the added weight on the fitting of the seal.

The B&K 4136 microphone has the following nominal characteristics

Directionality – omni-directional
Frequency response (nominal) – 4Hz – 70kHz
Maximum peak SPL – >172dB

2.2 Calibration

Both the Sennheisser and Knowles microphones are non-instrumentation microphones and do not lend themselves readily to field calibration. There may also be concerns about sensitivity changes in practical situations, so having a ready means to calibrate the devices is highly desirable. With the cylindrical Sennheisser, the problem was solved by making a coupler that allowed the microphone to be fitted into a quarter inch adapter on a B&K sound intensity calibrator, type 3541. This has provision for calibrating two microphones simultaneously using a type 4228 pistonphone and UA0914 coupler. With the Sennheisser and a standard ¼ inch microphone fitted into the upper chamber of the coupler, the same sound pressure level (117.9dB) was applied to each microphone. Knowing the sensitivity of the 1/4inch microphone it is possible to deduce that of the Sennheisser.

The Knowles microphone was more problematical since it is of square cross section. However, it was possible to manufacture an adapter allowing the microphone to be inserted in a B&K 4221 high-pressure calibrator. This is another device that has provision for the simultaneous calibration of two microphones and which may be used at relatively high sound levels and which will provide calibrations over an extended frequency range (20Hz to 1000Hz).

The B& K 4221 can also be operated at different sound pressures and provides a ready means for checking the upper limit of the miniature microphones

2.3 Measuring instrumentation

With the calibration methods solved, it is relatively easy to apply the resulting microphone signals to any conventional detection system. For the purpose of this exercise the signals were either measured on a B&K 2610 measuring amplifier, a B&K 2231 sound level meter or on a two channel Ono Sokki type 360 analyser. Use of the later allowed direct comparisons between two microphones in use at the same time as well as providing waveforms that were essential for checking that there was no distortion of the signals.

3 EXPERIMENTAL ARRANGEMENTS

3.1 Stimuli

Several different inputs were studied:

a) Tapping the cup with a piece of scaffolding pole also striking the upper part of the shell. Different weights of scaffolding pole were used but the taps were kept relatively light to simulate the accidental striking that could occur as a person climbs through scaffolding
b) Tapping cup with a pen: the cup was tapped with a plastic pen on the upper part of the shell. This was achieved with a light tap (accidental type) and a heavy type (deliberate type)
c) Banging cup: this was designed to replicate the many practical situations when the cup is struck against a protruding object such as a pipe, a doorframe, scaffolding or the side of a vehicle. The test was carried out by opening a wooden door onto the outer shell of the cup with an average impact.
d) Releasing/flicking the cup: The cup was pulled away from the head and ear to a distance of 25mm. The muff was then released so that it impacted squarely against the head/ear. As a variation, with some protectors, it was found that during the action of removing the muff it was easy to lose grip of a cup resulting in a flicking impact of the muff against the head.
e) Lifting cup: starting with the subject wearing the ear muffs with a good seal, the cup was lifted swiftly away from the head as it would be when the ear muff is removed in practice.
f) Jumping: to examine the levels inside the cup when the wearer was engaged in fast activity, the levels were measured with the wearer running up and down stairs and jumping from heights of 600mmm and 900mm.
g) With helmet: tests were carried out banging a standard safety helmet fitted with helmet-mounted protectors and a military helmet fitted over complementary protectors.

All the above tests were carried out in a consistent manner and without using excessive force that would not normally be encountered in practice. For example, when releasing the cup against the head, the release was not exaggerated in any way, or when tapping with a pen, the cup was tapped firmly but not "whacked".

3.2 Test samples

Examples of Peltor H7A and H10A hearing protectors were used, the former was adapted to carry the ¼ inch microphone. Additional tests were carried out with the Peltor NSNCH 4240-99-773-1232 fitted under a standard army issue helmet. For comparison, measurements were also made under the cups of MSA type “hi-lo” (black) protectors both in standard version and attached to a MSA safety helmet.

A number of events were recorded for each type of stimulus and protector using more than one person as the “passive” recipient. Precautions were taken against excessive noise entering the ear canal by the use of additional earplugs where appropriate.

3.3 Test technique

With the miniature microphones, measurements were made essentially using the technique described in [6]. The chosen microphone was held in place at the entrance to the ear canal just above the tragi with surgical tape and the wires led out under the cup seal, ensuring a good fit between the seal and the face. This system could be used on any muff or muff/helmet combination. As already stated the ¼ inch microphone had to be fitted through a hole drilled through the top of one cup of the Peltor H7s. The preamplifier was sealed into the hole with resilient sealant and held in place at the appropriate angle by tape to the headband, The microphone position was adjusted by trial and error until it was immediately opposite the entrance to the ear canal.

3.4 Transfer function

Measurements made under the cups using the MIRE technique have to be referenced back to the equivalent free field or diffuse field value to enable them to be compared with the action values or limit values. This procedure is described in detail in [6] and appropriate values are given. Although there may well be some debate over the interpretation of some of the legislation, it is preferable to include this transfer function when comparing these self-generated noise levels with criteria. However most of the inputs that generate noise under the cups which is dominated by low frequency energy components and at these frequencies the transfer function is less than 1dB whether in a diffuse or free field. Nevertheless this could be important in the final analysis as could the fact that the location of the microphone under the cup and particularly in close proximity to the ear canal can also influence the measured level especially in the measurement of peak levels where the phase relationships of the various components determines the final value.

4 RESULTS & DISCUSSION

It was obvious, by observing waveforms during the measurements that for many of the heavier stimuli the performance of the miniature microphones was inadequate since the signal overloaded. Greater reliance has had to be placed upon the data obtained from the ¼ inch microphone. The results given in table 1 is a selection drawn from the different microphones employed, working within their calibrated operating ranges and therefore they are mainly taken from the set made using the H7A protectors and the ¼ inch microphone. Where the stimuli induced lower levels it can be shown that the differences between ear muff types is not significant. A range of values has been given since the resultant peak level was influenced not only by muff type but also by the strength and nature of the stimulus.

Table 1

Ear Muff Type	Source Description	Range of Peak Levels (Lin), dB re 20:Pa	Range of Peak Levels (C), dB re 20:Pa	Range of ASEL, dB re 20:Pa
Peltor H7A	Banging with scaffold	140-150	138-146	97-103
Peltor H7A	Tap with pen	122-128	120-127	83-90
Peltor H7A	Tap heavily with pen	135-145		
Peltor H7A	Banging against door	135-147	128-140	83-95
Peltor H7A	Releasing on head	138-160	141-155	97-109
Peltor H7A	Lifting away from head	146-154	124-134	71-83
Peltor H7A	Jumping off chair	127-141	125-133	78-85
MSA with helmet	Jumping off chair	112-138	118-133	82-91
MSA with helmet	Banging with scaffold, top	132-136	131-136	96-101
MSA with helmet	Banging with scaffold, rim	132-139	134-140	100-107
Peltor NSN with army helmet	Banging with scaffold, top	126-132	129-133	94-99
Peltor NSN with army helmet	Banging with scaffold, rim	123-128	124-129	89-94
ATF & Peltor H7A	Tap heavily with pen	135-143		
ATF & Peltor H7A	Releasing on head	138-142		

Tapping/banging the muff with a length of scaffolding tube produced a simple decaying sinusoid (period ~ 10ms) with peak levels from 138dBC to 146dBC (fig.4). This range of sound levels and the waveform type covered blows from different scaffolding types with different but reasonable levels of severity. Lighter taps with a pen also produced a similar waveform but usually at a much lower level 120-127dBC. Deliberate hard blows on the top of the cup resulted in higher levels. There was some finer structure in the waveform, which gave a more impulsive look to the leading edge (fig 3). Banging the muff against a door produced peak levels below those found by banging with scaffolding (128-140dBC). The waveforms were significantly different giving the impression that, during the process of applying the stimulus, the door pushed the cup and compressed the seals and the inertia in the door maintained the compression for a time. Lifting the cup away from the head produced an easily repeatable pressure shift, initially negative going, in the range of 146-154dB (linear) but only 124-134dBC. The waveform could be identified by its clear, single deviation from the ambient level, followed by a smooth return to ambient (fig.1). Releasing the cup produced higher levels 138-160(linear) and 141-155dBC. The waveform varied slightly from that described above being slightly more complex and initially positive going (fig. 2).

The measurements also showed that an impact to a helmet did not readily transmit through to the defender and hence the ear (fig 7 & 8). The army issue helmet was rather better in this respect since the ear protectors were fitted across the head rather than directly to the helmet. The waveform showed a much longer decaying sinusoidal form (fig.7) than that obtained with the direct blow to the cups. Direct blows to the cups of course, produced similar results to those obtained without the helmets. There was also a noticeable difference whether the blow was delivered horizontally to the rim or vertically to the crown.

4.1 Comparison with NAWR

To allow comparisons with the first and second action levels in the NAWR [1] a selection of results were also analysed using the A weighting and presented as sound exposure levels (SEL). These are also given in table 1. In terms of Lepd these are relatively low level single events. For the highest level produced, by releasing the cup back to the ear (SEL 109dBA) a total of 363 events would be possible before the second action level was breached. Banging the cup with scaffolding which produced a maximum recorded SEL of 103dB could be carried out 1445 times before the second action level is breached. Clearly far more events than would be expected to occur on a casual basis in a day. However, in both instances the peak action level would have been exceeded.

Figure 1 - Lifting hearing defenders away from head, B&K 4136 mic under Peltor H7A defenders

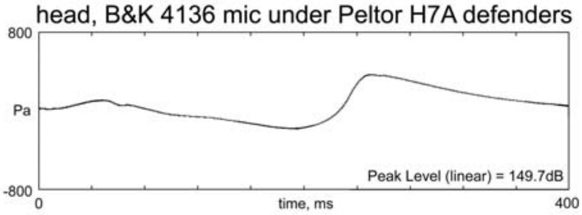


Figure 2 - Releasing defenders against head, B&K 4136 mic under Peltor H7A defenders

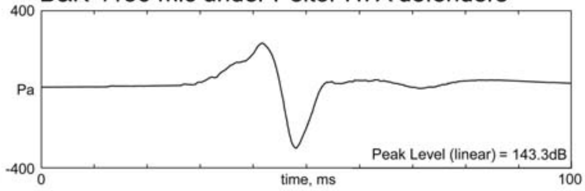


Figure 3 - Tapping defender cup with pen, Knowles microphone under H7A defenders

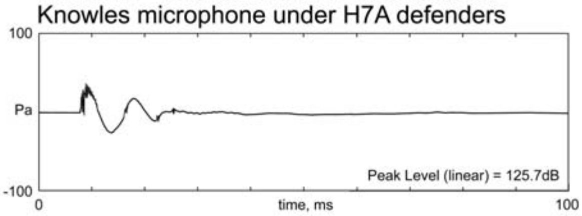


Figure 4 - Banging defender cup with scaffold tube, B&K 4136 mic under H7A defenders

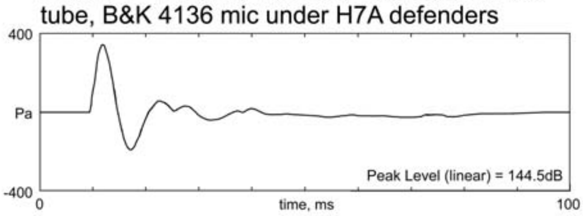


Figure 5 - Banging defender cup with small scaffold tube, B&K 4136 under H7A defenders.

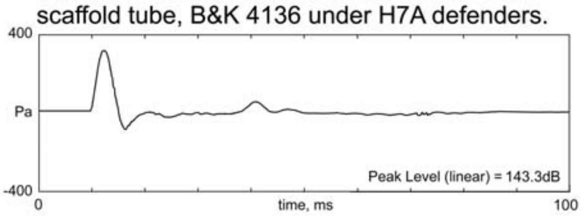


Figure 6 - Jumping off chair wearing defenders, B&K 4136 microphone under H7A defenders

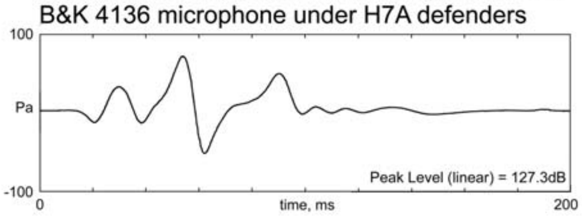


Figure 7 - Banging helmet with scaffold tube, Knowles mic under NSN defender & army helmet

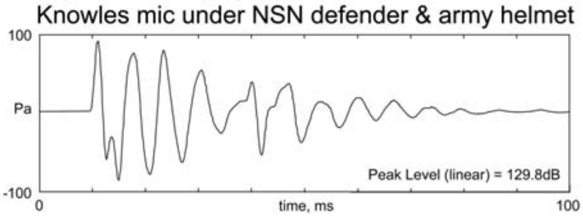
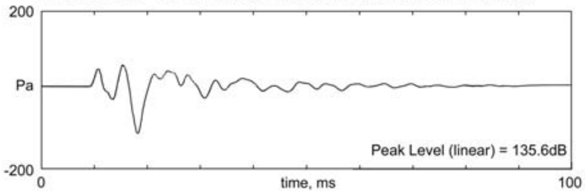


Figure 8 - Banging helmet with scaffold,Knowles mic under MSA defenders attached to helmet



4.2 Use of ATF

To check the validity of the data obtained from the 1/4inch “through the cup” microphone some measurements were repeated with the adapted hearing protector fitted on an ATF. The Acoustic Test Fixture (ATF) is an acoustic ear simulator used in the measurement of insertion loss of muff type protectors for quality inspection purposes [7]. It is a solid metal cylinder, mounted horizontally on a stand, with the end faces cut a slight angle to simulate the shape of the human head at the ear position. There is no attempt at reproducing both features of the ear canal or pinna but there is provision for flush mounting microphone at the point where the ear canal should be. The object of the tests was to compare the output of the ATF microphone with that obtained from the 1/4inch mic. The Salford ATF has been adapted to carry a resiliently mounted half inch B&K 4166 microphone. Since the various inputs applied to the muffs were essentially mechanical impacts there was a distinct danger that the resultant impulses could be transmitted directly into the ATF and to the microphone as vibration, despite the built-in resilience. Tests were carried out with the ATF microphone occluded by a sealed metal plate and these showed that there was at least an additional 10dB of isolation in that system.

Good agreement was obtained between the two microphones as can be seen in fig.9. Small differences can be attributed to the position of the microphones under the cup that as discussed in 3.4 can be critical when measuring peak pressure levels. Table 1 gives some additional results from tapping and lifting/releasing the muff when fitted on the ATF.

Figure 9 - Waveforms measured using the ATF with Peltor hearing defenders. *top:* B&K 4136 inside muff, *bottom:* B&K 4166 mounted in ATF.

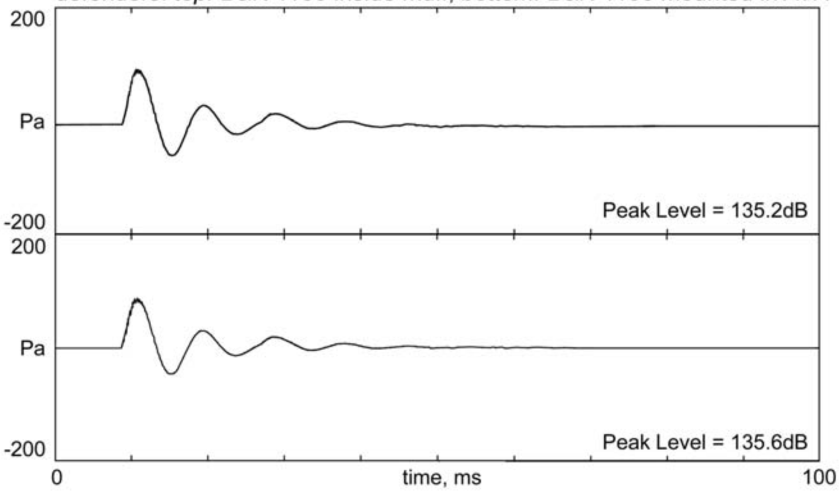


Figure 10 - Comparison between waveforms measured with different microphones under H7A defenders when tapped with pen.
top: B&K 4136, *bottom:* Sennheiser MKE 2-4 Gold C

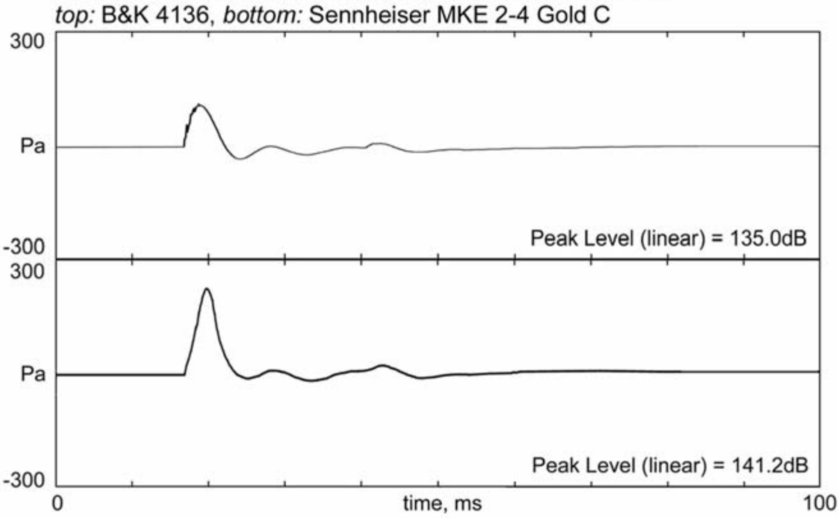
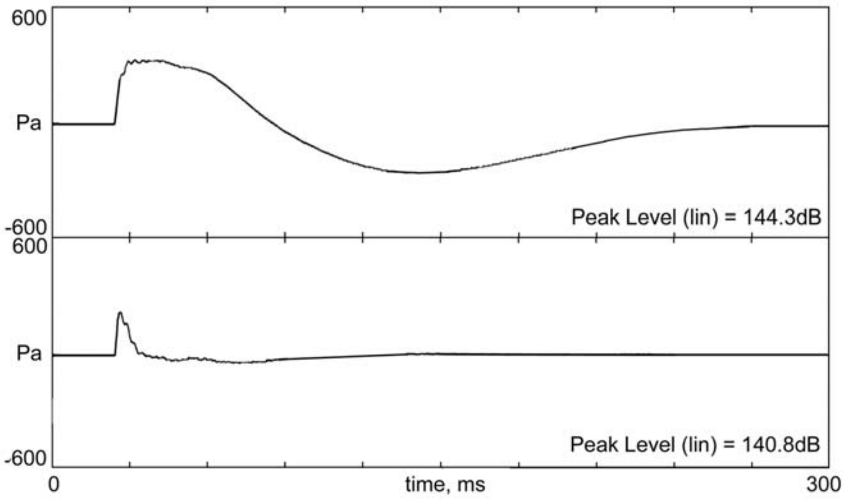


Figure 11 - Comparison between waveforms recorded with different microphones, demonstrating the Knowles' low frequency limitations.
top: B&K 4136, *bottom:* Knowles.



4.3 Miniature Microphones

The response of both miniature microphones was disappointing. Early checks involving the investigation of waveforms indicated significant differences between the waveforms obtained with both miniature microphones and the ¼ inch microphone. In the case of the Sennheisser, we observed significant differences between the positive and negative going phases that in some cases showed well before the assumed upper dynamic limit was reached (fig.10). This was attributed to non- linearities in the operation of the diaphragm in the charge field at the extremes of its range. Below this level the microphone operated satisfactorily, was easy to calibrate and the extended low frequency response resulted in waveforms that were very similar to those obtained with the ¼ inch microphone.
The Knowles microphone performed in a linear manner to its expected 144dB limit but the effects of the limits of its low frequency performance, below 100Hz, were clear in some comparisons, (Fig 11).

5 CONCLUSIONS

This investigation has demonstrated that knocks and bumps can generate noise levels at the ear in excess of 140dBC during normal use of muff type hearing protectors. The highest levels were produced when the cup was pulled away from the head and released. Safety helmets tended to reduce the impact to muffs which were directly mounted, and the standard issue army helmet considerably reduced the effects of impacts on the fitted ear defenders. To obtain these results a range of microphones were used and limitations in performance have meant that the more important results have had to be taken using an arrangement that is far from ideal. A single miniature microphone is required that can be readily calibrated in the field, can be used under the cup using MIRE technique and which has both a broadband performance and a large dynamic range. Such a microphone would not only facilitate the assessment of this type of “self-generated” noise but also the selection of hearing protection for use in impulsive noise. The project has also highlighted a requirement to identify the experimental limitations when determining the exposure to peak sound levels produced under ear protection at and around the (peak) exposure limit value.

6 REFERENCES

1. Noise at Work Regulations 1989, SI 1989 No. 1790, HMSO
2. Directive 2003/10/Ecof the European Parliament and of the Council, 6 February 2003.
3. BS EN 24869-1: 1992 Acoustics-Hearing protectors-Part 1: subjective method for the measurement of sound attenuation (ISO 4869-1:1990).
4. Assessment of hearing protector performance in impulsive noise. Final report. G.F.Smoorenburg, TNO-report TM-96-CO42, 13 November 1996
5. BS EN 458:1994 Hearing Protectors - Recommendations for selection, use, care and maintenance – Guidance Document
6. BS EN ISO 11904-1:2002 Acoustics-Determination of sound emission from sound sources placed close to the ear – Part 1: Technique using a microphone on a real ear (MIRE technique)
7. BS EN 24869-3: 1994 Acoustics – Hearing Protectors – Part 3: Simplified Method for Measurement of Insertion Loss of Ear Muff Type Protectors for Quality Inspection Purposes

7 ACKNOWLWDGEMENT

This work was supported by the UK Ministry of Defence (MOD) however the views expressed in this paper are based on the professional experience of the authors and may neither reflect the MOD’s view nor be binding upon the Ministry.