Recent developments in firearms noise and hearing conservation: hearing protection fit testing, noise measurement and hearing surveillance

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Abstract

Background. Noise induced hearing loss (NIHL) continues to be a prevalent problem in Military Service.

Purpose. To assess the 'SureFire' earplug, a hearing protective device (HPD), within the context of a hearing conservation programme.

Methods. The 'VeriPro' system was used to test the HPD attenuation, with otoacoustic emission (OAE) 'baseline' hearing tests. Noise exposure was measured during test firing, and a post exposure OAE test was carried out to measure any deterioration in hearing due to excess noise exposure.

Results. Better attenuation was achieved in right ears. The HPDs were rated to reduce the noise by at least 15 dB in 84% of those exposed, the actual attenuation lying in the range between 8.4 and 23.6 dBA. The median noise level was 110 dBA. The OAE testing did not show any significant before and after differences.

Discussion. Some individuals achieved good HPD fit, some quite poor. The average noise levels received were excessive, but the daily noise dose was within acceptable limits because of the short duration of exposure, possibly explaining the non-significant differences in OAEs. We recommend that individuals should only use HPDs which are 'fit proven'. Additional testing under more typical conditions with a larger group is required, but OAEs show promise as a practical monitoring tool.

Conflicts of interest. None.

Introduction

The noise exposure from weapons systems is a problem in the military because of the extreme levels of noise involved and the competing requirements for protection on the one hand and situational awareness on the other. Three essential components of military hearing conservation programmes have presented technical difficulties: noise measurement, the assessment of hearing protection 'effectiveness' and hearing surveillance.

Firstly, a bench-mark exposure standard is needed to indicate excess exposure. The impulse noise exposure standards are different from the continuous standards both in terms of how they have been set and what needs to be measured. The continuous noise standards are a sound pressure level (SPL) of 85 dBA over a period of 8 hours, with an equal energy relationship so that 88 dBA for 4 hours (double the SPL) is also 100% of the dose.[1] This standard was set by looking at the permanent hearing loss (permanent threshold shift, PTS) found in workers exposed to these levels of noise over long periods. It does not prevent, but limits the prevalence of, noise- induced hearing loss. The duration of the impulse noise from firearms is in the order of a few milliseconds and there is a limit to which the equal energy hypothesis can be extrapolated for such very short time durations. A 'peak' exposure standard of 140 dB has been adopted by many countries including New Zealand,[2] primarily because, in excess of this level, the behaviour of the sound field is different and requires special measurement techniques. Impulse energy is also measured by level, the peak level, and an "energy like" measure of duration, of which there are a number. The "B" duration, where the impulse has fallen 20 dB from the peak, is an example: it is identifying this parameter which requires special equipment. Because impulse noise is more unpredictable in terms of long term exposure, the effects were looked at in terms of the temporary hearing loss (temporary threshold shift, TTS) that occurs directly after noise exposure, the TTS or risk of hearing loss being different for each impulse noise parameter. A number of impulse noise exposure criteria have been developed. Amongst the first in the 1960's, and illustrative of the concept, is that of Coles et al[3] with a limit of 159 dB Lpeak for 5 ms, the exposure being limited to 100 rounds fired at rates of between 6 and 30 per minute. This should limit the TTS to be not more than 10 dB at or below 1000 Hz, 15 dB at 2000 Hz, and 20 dB at or above 3000 Hz in 75% of the normal hearing persons exposed. The continuous and impulse standards are not entirely congruous in terms of both "equivalent energy" and the likelihood of harm, but more recently the sound exposure level, the SPL normalised to 1 second, has been proposed as a unifying metric.[4] The limit is a critical level of 116 dBA SEL per impulse, with 50 exposures allowed. This should not result in a TTS_2 (the TTS measured 2 minutes after exposure) of greater than 25 dB HL at 4 and 6 kHz in 95% of those exposed. This limit has the advantage that it can be measured with a standard sound level meter.

Secondly, because of the need for situational awareness, HPDs are inconsistently used. Many solutions have been proposed to the situational awareness conundrum, including noise cancelling communications systems and "non linear" HPDs. In theory, these methods should all work effectively because they have been laboratory tested. The drawback is however that hearing protection seldom achieves the rated attenuation in practice. This depends on whether an individual fits hearing protection effectively, all HPDs being affected to a greater or lesser extent, but a particular problem with earplugs. It is however now possible to perform a "fit-test" by measuring the attenuation that an individual achieves in the clinic by using a simple pure tone loudness balance test.

Thirdly, even if fit-testing has been carried out, the only way to detect if hearing protection is working properly under actual exposure conditions is to check whether the individual has a temporary reduction in hearing ability, a TTS which indicates excessive exposure. A TTS can be detected with an audiometric test before (base-line test) and after (monitoring test) noise exposure, this being the New Zealand Department of Labour recommended screening procedure.[2] The difficulty is the time required for the post exposure test which is in the order of 10 minutes, a rate limiting step in any practical application. The other problem is the behavioural nature of the test, which shows significant test-retest variability, the test-retest standard deviation (SD^{diff}) being of the order of 6-10 dB hearing level (HL).[5] As the TTS is likely to be in the order of 10-20 dB HL this has obvious implications for the validity of audiometric screening. A more recent development lies in otoacoustic emissions (OAE) testing. Distortion product (DP) OAEs are produced by applying two primary tones at different frequencies through an insert earpiece to the ear. The ear responds, most likely due to an active response by the outer hair cells of the cochlea, with an output which can be detected by a microphone in the same earpiece. Subsequent computer processing produces a "DP gram" which can be interpreted, within limitations, like an audiogram. This test is rapid, taking in the order of 3-4 minutes, and is entirely passive. It also has better test-retest variability, with reported SD^{diff} of 2 dB,[6] and may thus have better validity in screening for TTS.

The aims of this project were to field test the relatively novel methods of measuring impulse noise exposure, assessing HPD fit, and detecting TTS in order to assess their utility for incorporation into the NZ Army Hearing Conservation Programme.

Methods

A cross sectional survey of an infantry platoon due to undertake test firing with the NZ individual weapon, the 5.56 mm Steyr Rifle (IW Steyr) on an a outdoor 25 metre range.

Pre-noise exposure fit verification of the "SureFire" standard issue earplug was undertaken with the Howard Leight 'VeriPRO' system. This uses a loudness balance algorithm, the subject first being tested with pure tones through headphones with no hearing protection, balancing the loudness. The subject then fits the right earplug and the amount by which the sound intensity must be increased to "re-balance" is equal to the attenuation for that ear. The test is then carried out in a similar way in the other ear.

The specification of the 'SureFire' plug includes a noise reduction rating (NRR) value, which is a measure of "real ear" attenuation measured across the spectrum 0.125, 0.25, 0.5, 1, 2, 3, 4, 6 and 8 kHz in laboratory volunteers. The NRR is published incorporating correction factors for the spectrum weighting type (A or C) and also incorporates variability measures. The result is a single number rating independent of the noise spectrum in question.[7]

Equation 1 is used to determine the level to which the HPD will attenuate the noise.

Equation 1

Attenuated exposure = Noise Level in dBA - (Protector NRR - 7 dB)

Noise exposure was measured using a Brüjel and Kjær type 2260 type 1 (precision) sound level meter, hand held near the firer's ear. Data included SELs, and SPLs in dBA for the duration of each shoot. Octave band analyses were performed to determine where the energy was distributed in the spectrum.

The noise dose is calculated using equation 2.

Equation 2

Dose = 100 × T/8 × 10(Leq-85/10)

Where T = exposure in hours

Pre and post OAE testing was performed using the Otodynamics Echoport ILO292 USB-II system with analysis by the Otodynamics ILO V6 clinical software.[8] The two primary tones, f1 and f2, were set at a ratio of 1.22 (f2>f1) with levels (also f2>f1) at 65 and 55 dB respectively.

The tests were carried out in the audiometry room of the Regimental Aid Post, or for post exposure tests in an audiometric booth mounted in a sound insulated trailer.

Descriptive and inferential statistical analyses were carried out using IBM SPSS v20.9 As noise level measurements are logarithmic values, central tendencies are presented as medians and distributions as inter-quartile ranges (Quartile 1 cut-point lower 25% of data and quartile 3 upper 25% of data). Means and standard deviations (SDs) were calculated for the 'VeriPRO' attenuation data. The noise spectrum with the highest overall Leq was then chosen as "worst case", and the mean-1 SD (for the appropriate frequency and ear) was subtracted from the mean of each octave band value to calculate the SPL that would be expected, with hearing protection, at that frequency in 84% of the population, the 'assumed protective value', APV.[7]

As the attenuation and OAE data conformed reasonably to normal distributions t-tests were used in between ears comparisons for 'VeriPro' testing and for pre- and post- exposure OAE differences.

Results

Thirty one individuals attended the pre-exposure assessments, fourteen (45%) returning to carry out the shoot and thus being available for noise exposure assessments and post exposure OAE testing. They were all male, of mean age 22.5 years, SD 2.15 years. Table 1 shows the noise exposure metrics. The median SEL for each shot was 114 dBA (inter quartile range (IQR) 1; median level equivalent (Leq) during the shoot 110.5 dBA, IQR 1.8; median duration 190 seconds, IQR 114.7; median SEL 133.2 dBA, IQR 4.8 and median exposure dose 135%, IQR 142.8%.

Table 1. Noise Exposure Metrics

Metric	Leq(t)dBA	t (sec)	Noise dose (%)
Median	110.5	190.0	135.0
Min	109.5	62.0	45.1
Max	112.5	252.0	284.6
Q1	110.1	115.3	71.8
Q3	111.9	230.0	214.6

The frequency spectrum of a the test with the highest Leq value (of 112.5 dBA) is shown in figure 1. The maximum part of the energy lay between

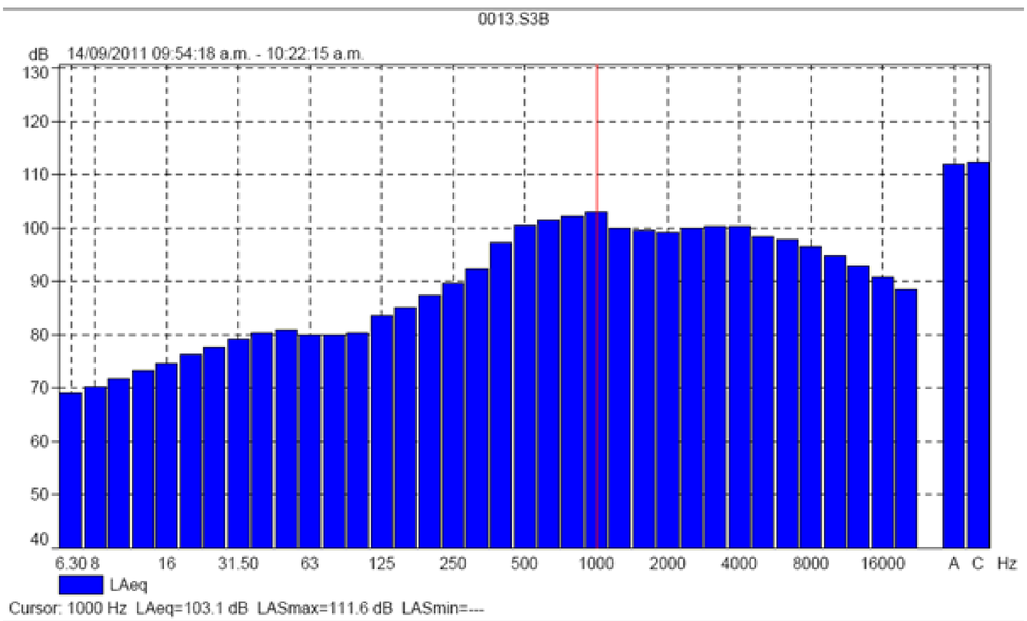

Figure 1. Frequency spectrum of a single shot.

approximately 400Hz and 6 kHz, the mode being 103 dBA at 1 kHz.

The 'SureFire' earplug has a NRR of 22, and, using equation 1, should reduce the median exposure (110 dBA) to a level of 95 dBA.

The VeriPRO data is shown as boxplots in figure 2: the boxes representing the 1st and 3rd quartiles; the bar within the box the median; the tips of the whiskers the maximum and minimum and the circles "outliers". The mean logarithmic attenuation across all frequencies was 16 dB HL, average SD / 7.6 dB HL, a minimum of 0 dB and a maximum of 35 dB HL. Eighty four percent of individuals would have achieved attenuation between ± 1 SD, or between 8.4-23.6 dBA. The test tended to show poorer attenuation in the left ear, but the only significant differences were at 1kHz (7.0 dB HL, p<0.001) and 2 kHz (4.9 dB HL, p=0.001).

Table 2. Assumed protective values of "SureFire" eagplugs

Ear	Right					Left				
Frequency	250	500	1000	2000	4000	250	500	1000	2000	4000
SPL	90	101	103	100	101	90	101	103	100	101
Mean attenuation	10.7	13.3	18.1	17.3	16.1	7.1	11.9	11.1	12.4	10.5
SD of mean	7.7	8.8	6.9	8.9	6.5	4.3	9.0	6.9	9.3	7.1
Estimated noise1*	87.1	96.5	91.8	91.7	91.4	87.2	98.1	98.8	96.9	97.6

(Footnotes) * SPL – Mean attenuation + 1 SD

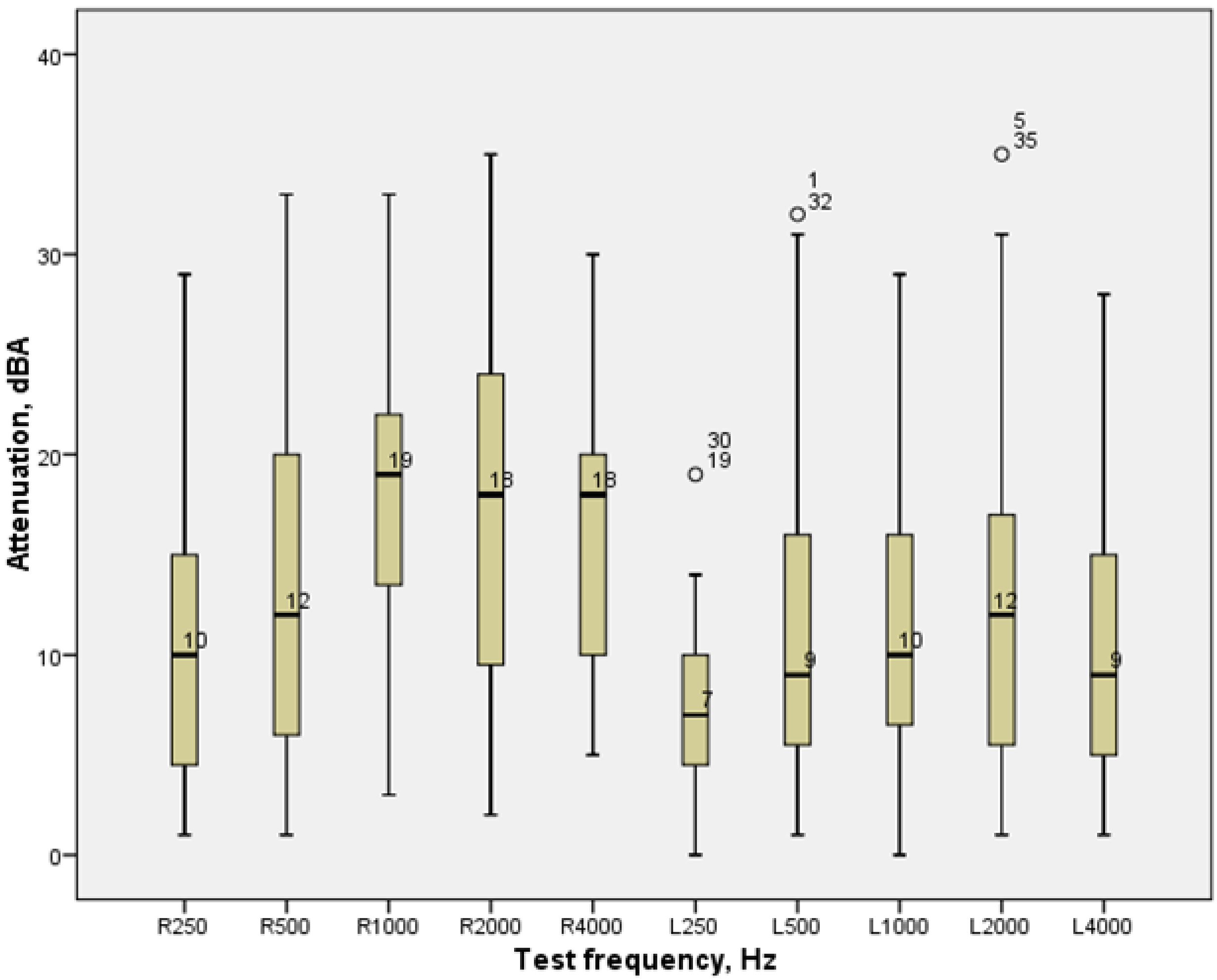

Figure 2. VeriPRO noise attenuation data.

Table 2 shows the APVs at each frequency, with a logarithmic average of 93 dBA for the right ear and 97 for the left.

Twelve soldiers completed both pre and post-exposure OAE testing, the pre and post exposure data being shown in figure 3, in which positive values indicates that the post firing OAEs had a reduced amplitude ("worse" second test). Conversely, if the second test had increased amplitude ("better" second test) the values would tend to be negative. The only statistically significant difference was at a frequency of 2.8 kHz in the left ear, where the pre-post test difference was 4.6 dB (p=0.04).

Discussion

This project, even though it took a simplistic view of the noise exposures, gives somewhat complex results. The noise exposure from this single practice of 25 rounds of standard 5.56 mm ammunition showed median unprotected levels of 110.5 dBA, median duration 3 minutes and 10 seconds. When this is extrapolated to an 8 hour day it would give rise to a median noise dose of 135%, just in excess of the continuous noise exposure standard. The levels did vary, the majority of exposures, as represented by the upper and lower quartiles of the distribution, lying between 72 and 215% of the allowable dose.

The VeriPRO fit attenuation data showed that, although there was no overall statistically significant "between ears" difference, the attenuation was poorer in left ears. The actual sound pressure level received by 84% of individuals would have been up to 93 dBA in the right ear and 97 dBA in the left.

There was no significant difference between the pre and post test OAE tests, the differences being small in magnitude.

The strength of the study was that the procedures were carried out in a realistic training scenario, and represent what could reasonably and practically be achieved in terms of incorporation into a hearing conservation programme. The major weakness was the small number of individuals who attended for second tests. This reduced the power in statistical comparisons, but should not otherwise have biased the results, the non-attenders being detailed for

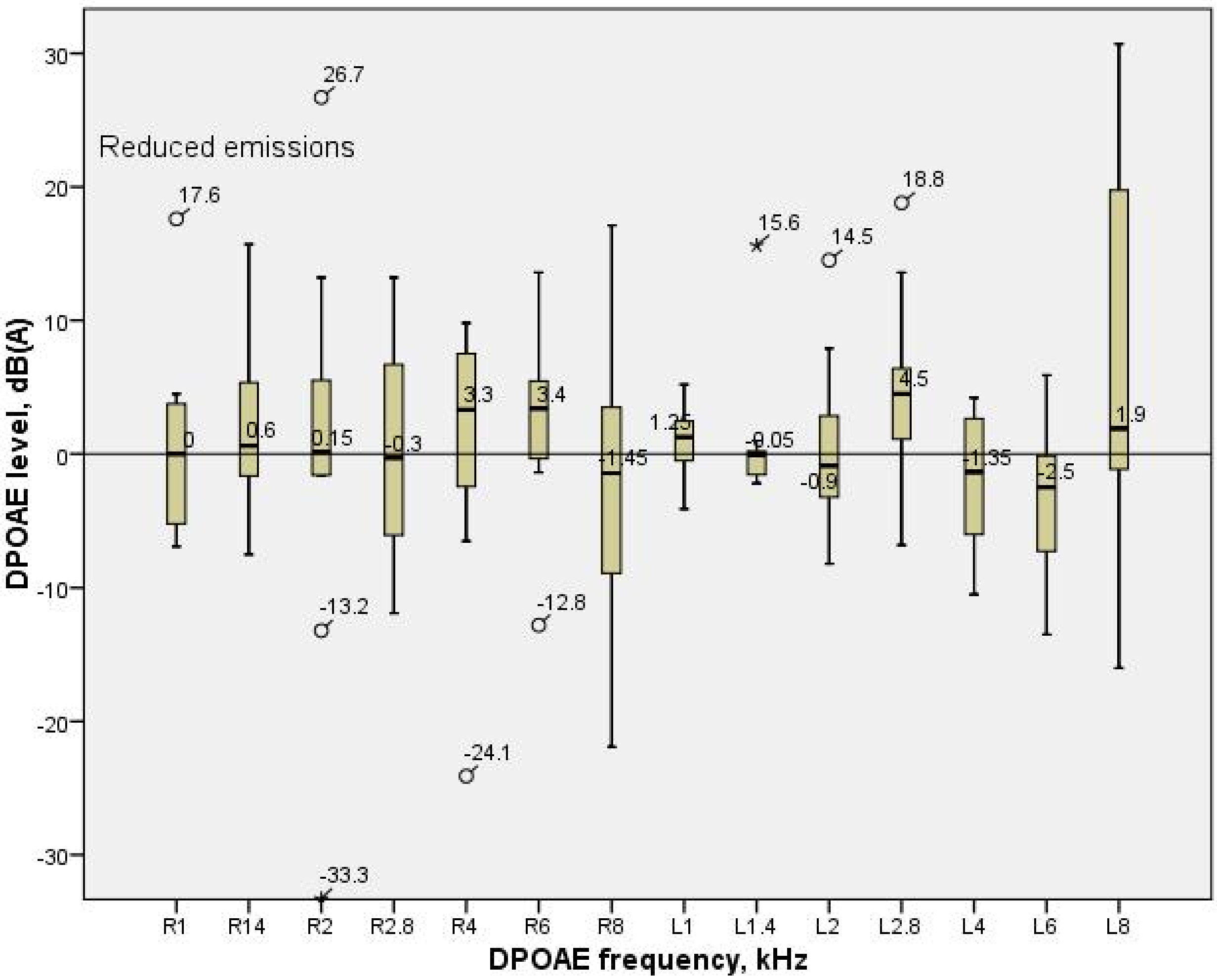

Figure 3. Differences between pre and post-exposure otocaoustic emissions.

other duties in what was probably a random fashion. The noise levels being measured were also in excess of the range of the noise meters used which would have reduced the exposure estimates.

Direct comparisons with other impulse noise studies can be difficult in that the results are usually given in terms of Lpeak and duration. A comprehensive assessment of firearms noise (.30-06 rifles, 0.38 revolvers and a shotgun) was however carried out by Flamme et al[10] and SELs are quoted. Measurements were carried out using controlled conditions, including the use of tripods and rests to ensure fixed microphone positions. The noise levels were very sensitive to firearm type, ammunition load and microphone position, SELs recorded ranging between 119 and 127 dBA. Previous tests by the author (unpublished data) with the Steyr, in a similar environment using noise dosimeters, showed median Leqs of between 111 and 112 dBA, and SELs of 112 to 113 dBA, similar to the results here. On the other hand, measurements taken during "jungle lane" shoots in a close country environment were considerably higher, with levels between 109-119 dBA. The levels will always be extremely sensitive to the acoustic environment, which is in fact a characteristic of impulse noise exposure.

The 'VeriPRO' between ears difference has not been reported in other published studies. In the test, the right ear is occluded first, the sound balanced and then the left ear is occluded. This may be a practice effect, may simply be due to chance or indeed an artefact. The failure to achieve the rated NRR is not at all unusual, a previous study of Australian aircrew showed that earplugs with an NRR of 32 had a group mean attenuation of only 15 dB.[11]

If the noise was excessive, an effect on hearing would have been expected. The SELs of 114 dBA recorded were however less than the NATO study group critical level of 116 dBA SEL per impulse, and the number of rounds was less than the allowable total of 50. The 25 rounds of exposure might therefore have been within the limits of the protection. Other studies have shown differences, that of Balatsouras et al[12] showing significant reduction in OAEs: 8.1 dB decrease at 3.003 kHz and 7.5 dB at 5.005 kHz in right ears, with left ears worse by 7.2 dB at 2.002 kHz and 7.4 dB at 3.003 kHz.

The noise levels in this study were high, very few occupations apart from military personnel, for example forestry workers and loggers, being exposed to noise in excess of 105 dBA.[13] While an 'equal energy' relationship is assumed, there is no reason to suppose that the response of the ear is linear. Physiologically, for example with the tympanic membrane 'mechanical' mechanism, the ear has a linear response to sound up to about 110 dBA,[14] the level found here, so the exposure may be 'safe' with no effect on OAEs. On the other hand we really do not know what the 'critical level' is. This was not however a typical shoot, the New Zealand Annual Personal Weapons Test consisting of 18 serials and a total of 98 rounds of 5.56 mm ammunition fired over a period of approximately 15 minutes. This would give a noise dose of 400% or more. Weapons with a more rapid rate of fire such as the C9 Minimi light support weapon or larger calibre weapons such as the 50 calibre heavy machine gun will require the use of double protection such as plugs and earmuffs.

The principal recommendations from this study are that much more attention to the fitting of earplugs is required. If individuals cannot demonstrate an adequate fit with training, then alternative methods should be sought until such time as attenuation is found to be adequate. If HP is worn, then the monitoring of hearing is mandatory, best practice being a test directly after noise exposure has occurred. This is designed simply to detect a change in hearing status which should in turn trigger an investigation into why this has occurred. OAEs seem to be an ideal solution to this, as the test is quick, minimally disruptive to training and should therefore be acceptable to commanders. To be useful in a screening programme further research and development is needed, particularly the most suitable test algorithm to use in terms of OAE frequencies, levels and ratios, and also what constitutes a 'significant emission shift, (SES)' the latter to trigger further intervention. A definition for SES needs to be developed by either using test-retest variability in the test group, or using the standard error of measurement in a control group.[15] We intend to pursue this, as it does seems that OAEs are predictive of incipient noise induced hearing loss.[15] We must learn how to use this technology successfully.

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