Diagnosis and quantification of military noise-induced hearing loss

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Abstract

The diagnosis and quantification of noise-induced hearing loss (NIHL) in a medico-legal context are usually based on the pattern of hearing loss that is typically associated with long-term exposure to steady broadband noises, such as occur in noisy factories. Evidence is reviewed showing that this pattern is not typical for hearing loss produced by intense impulsive sounds of the type that military personnel are exposed to. The audiometric characteristics of noise-exposed military personnel are reviewed. A set of audiograms from a sample of 58 hearing-impaired noise-exposed military veterans was analyzed and used to develop methods for the diagnosis and quantification of military NIHL. Three requirements are specified for diagnosing military NIHL. Quantification of any loss is done by comparison with audiometric thresholds for non-noise exposed individuals, as specified in ISO7029 [International Organization for Standardization, 2017].

I. INTRODUCTION

Noise-induced hearing loss (NIHL) can occur as a result of exposure to sounds with levels over about 85 dBA (National Institute for Occupational Safety and Health, 2020) or 80 dBA (European Parliament, 2003). It has been estimated that approximately 15% of people in the USA aged 20 to 69 years display hearing impairment that may have been caused by exposure to noise at work or during leisure-time activities (Hoffman *et al.*, 2017), that 33% of working-age adults with a history of occupational noise exposure have audiometric evidence of noise-induced hearing damage, and that 16% of noise-exposed workers have material hearing impairment (Themann and Masterson, 2019). Occupational NIHL occurs mainly for people who work in mining, construction, manufacturing, and the military (Themann and Masterson, 2019). The incidence of NIHL in most sectors of manufacturing has been diminishing, partly because of stricter regulations about hearing protection, for example the use of earplugs and earmuffs, although the incidence in mining and construction remains high (Masterson *et al.*, 2015). Although hearing protection is routinely supplied to military personnel, it is often not used in active service because of the need to hear warning signals and instructions. Hence, NIHL among military personnel remains a serious problem (Themann and Masterson, 2019). This paper presents evidence indicating that the methods typically used to diagnose and quantify NIHL are not appropriate for NIHL in military personnel and suggests alternative methods of diagnosis and quantification.

People with occupational NIHL may claim compensation from their employer. This requires diagnosis and quantification of the NIHL, usually by a medical expert. In the UK, the diagnosis of NIHL is usually done following the guidelines of Coles, Lutman and Buffin (Coles *et al.*, 2000), referred to here as the CLB method. Similar methods are used in other countries, including the USA (Dobie, 2011). Quantification in the UK is sometimes, but not always, based on the guidelines of Lutman, Coles and Buffin (Lutman *et al.*, 2016), referred to here as the LCB method. The CLB and LCB methods were designed to be appropriate for the NIHL that occurs following long-term exposure to the type of broadband noise that typically occurs in factories. This is associated with a “notch” or a “bulge” in the audiogram, most commonly centered at 3, 4 or 6 kHz and with only a small threshold elevation at 8 kHz, unless the NIHL is severe (Passchier-Vermeer, 1974; Robinson, 1985; Smoorenburg, 1992). Of course, the notch or bulge may not be apparent if the hearing threshold level (HTL) at 8 kHz is not measured, as is often the case for occupational audiograms. Both the CLB and the LCB methods depend on the use of audiometric thresholds at "anchor points" (also called "references") of 1 and 8 kHz, which are assumed to be relatively unaffected by the noise exposure. In this paper, it is argued that the CLB and LCB methods are not appropriate in cases of military noise exposure, which typically involve very high sound levels and include exposure to highly impulsive sounds (Jokel *et al.*, 2019). A set of audiograms from 58 hearing-impaired military veterans is analyzed and used as the basis for developing and evaluating alternative methods of diagnosis and quantification.

II. EXISTING METHODS FOR DIAGNOSIS AND QUANTIFICATION OF NIHL

A. The CLB diagnostic method

The CLB method for diagnosing NIHL is based on three requirements, together with some modifying factors (Coles *et al.*, 2000). The requirements are as follows:

R1. There should be evidence for a high-frequency hearing loss. The specific criterion is: "when a single measurement of hearing threshold level (HTL) at 3, 4 or 6 kHz … is at least 10 dB greater than the HTL at 1 kHz or 2 kHz".

R2. There should be sufficient noise exposure. This can be established in two ways: R2a "At least 50% of individuals exposed to this known or estimated amount of noise would be likely to suffer a measurable degree of hearing loss". This requires "an equivalent daily 8-h continuous noise exposure (L_{EP}, d) of not less than 85 dB(A) for a sufficient number of years to lead to a cumulative exposure of at least 100 dB(A) NIL (Noise Immission Level)". The alternative is R2b "A less stringent noise exposure requirement is applicable provided the audiometric evidence of noise damage is stronger. The lower level of total noise exposure for such cases is reduced to 90 dB(A) NIL".

R3. There should be a downward notch or bulge in the audiogram in the range 3-6 kHz. A notch is defined as present when "the hearing threshold level (HTL) at 3 and/or 4 and/or 6 kHz …. is at least 10 dB greater than at 1 or 2 kHz and at 6 or 8 kHz". A bulge is defined as present when “the HTL at 3 and/or 4 and/or 6 kHz … is at least 10 dB greater relative to the comparison values for age-related hearing loss at corresponding frequencies.”

To establish whether R3 is satisfied, it is customary to undertake a “bulge analysis” using the HTLs at 1 and 8 kHz as anchor points. R3 is based on the assumption that NIHL will typically result in greater hearing loss at 4 than at 8 kHz. Table I shows an example of a bulge analysis. The age-associated hearing loss (AAHL) values are those for a man without noise exposure aged 50 years at the 50th percentile. The measured HTL at 1 kHz is 4 dB higher than the AAHL value, while the HTL at 8 kHz is 10 dB higher than the AAHL value. These are denoted “misfit values”. They indicate the extent to which the AAHL values at the anchor points differ from the measured HTLs. The misfit values are interpolated across frequency on a logarithmic frequency scale (line D) and used to give adjusted AAHL values (the sum of rows C and D). These adjusted AAHL values are set equal to the measured HTL when they are greater (worse) than the measured HTL, since noise exposure does not improve audiometric thresholds. The differences between the adjusted AAHL values and the measured HTLs are shown in the bottom line of the table; these correspond to the estimated NIHL. Any value exceeding 10 dB at 3, 4, or 6 kHz qualifies as a bulge. The magnitude of the bulge in this example reaches 15 dB at 4 kHz and 11 dB at 6 kHz, so R3 is satisfied.

Table I. Example of a bulge analysis using the CLB method. Values in specific lines are denoted A, B, C, D, and E.

	Coles et al 2000 method						
	Frequency, kHz	1	2	3	4	6	8
A	Hearing threshold level (HTL), dB HL	10	10	15	45	45	40
B	HTL at selected anchor points	10					40
C	Selected age-associated hearing loss (AAHL)	6	11	15	22	25	30
	Misfit values (dB) = B - C at anchor points	4					10
D	Interpolated misfit values (dB)	4	6	7	8	9	10
	Adjusted AAHL = C + D	10	17	22	30	34	40
	Set AAHL to 0 when AAHL<0	10	17	22	30	34	40
E	Set AAHL to actual when AAHL>actual	10	10	15	30	34	40
	NIHL, i.e. bulge (dB) = A - E	0	0	0	15	11	0

B. The LCB method for quantification of NIHL

The LCB method for quantifying NIHL involves two "passes". Pass one is the same as the CLB "bulge analysis", described above, using anchor points at 1 and 8 kHz. Pass two involves the following steps, which are illustrated in Table II using the same audiometric thresholds as for Table I and using the same AAHL values:

(1) Estimation of the extent to which the audiometric thresholds at the anchor points include some NIHL, based largely on the data of Passchier-Vermeer (1974). The NIHL value at 1 kHz is calculated as 0.15 times the estimated NIHL at 4 kHz obtained in the first pass. Similarly, the NIHL value at 8 kHz is calculated as 0.4 times the estimated NIHL at 4 kHz (line F in Table III).

(2) Altering the measured HTLs to create modified HTLs at the anchor points, by subtracting the estimated NIHL values from the measured HTLs (line G).

(3) Selecting AAHL values to give a good match to the modified HTLs at the anchor points (line H). In the example given, the AAHL values are the same as for the first pass (line C), but they could in principle be different, if a different percentile is chosen.

(4) Calculating "misfit values" at the anchor points, which are the differences between the modified HTLs (Line G) and the AAHL values (line H), giving the values in line I.

(5) Interpolation of the misfit values in line I on a logarithmic frequency scale to give misfit values at all frequencies (line J).

(6) Calculation of modified AAHL values by adding the AAHL values in line H to the interpolated misfit values in line J, giving line K.

(7) Setting the modified AAHL values in line K to 0 when they are negative (line L).

(8) Setting the modified AAHL values in line L to the measured HTLs when the modified AAHL values are greater than the measured HTLs (line M).

(9) Quantifying NIHL as the difference between the measured HTLs (line A) and the values in line M, giving line N.

For the example shown in Table II, the estimated NIHL is 0.7 dB when averaged across 1, 2, and 3 kHz, and 7.3 dB when averaged over 1, 2, and 4 kHz. The issue of what frequencies to average across for estimating the overall NIHL is discussed in section VI.B.

Table II. Example of a two-pass analysis using the LCB method. Values in specific lines are denoted A to N.

	Lutman et al 2016 method		Frequency, kHz					
	Pass 1 (same as table I)		1	2	3	4	6	8
A	Hearing threshold level (HTL), dB HL		10	10	15	45	45	40
B	HTL at selected anchor points		10					40
C	Selected age-associated hearing loss (AAHL)		6	11	15	22	25	30
	Misfit values (dB) = B – C at anchor points		4					10
D	Interpolated misfit values (dB)		4	6	7	8	9	10
	Adjusted AAHL = C + D		10	17	22	30	34	40
	Set AAHL to 0 when AAHL<0		10	17	22	30	34	40
E	Set AAHL to actual when AAHL>actual		10	10	15	30	34	40
	NIHL (dB) = A - E		0.0	0.0	0.0	15	11	0
	Pass 2							
F	Estimate NIHL at anchor points (dB)		2.2					6
G	Modified HTL at anchor points (dB HL) = A – F		7.8					34
H	Selected age-associated hearing loss (AAHL)		6	11	15	22	25	30
I	Misfit values (dB) at anchor points = G – H		1.8					4
J	Interpolated misfit values (dB)		1.8	2.5	2.9	3.3	3.6	4.0
K	Modified AAHL (dB) = H + J		7.8	13.5	17.9	25.3	28.6	34.0
L	Set AAHL to 0 when AAHL<0		7.8	13.5	17.9	25.3	28.6	34.0
M	Set AAHL to actual HTL when AAHL>actual		7.8	10.0	15.0	25.3	28.6	34.0
N	NIHL (dB) = A – M		2.2	0.0	0.0	19.7	16.4	6.0
	Mean NIHL at 1, 2 and 3 kHz, dB	0.7						
	Mean NIHL at 1, 2 and 4 kHz, dB	7.3						

III. PREVIOUS DATA ON THE AUDIOMETRIC CHARATERISTICS OF PEOPLE EXPOSED TO NOISE DURING MILITARY SERVICE

Both the CLB and LCB methods depend on the assumption that noise exposure has only a small effect on HTLs at 8 kHz. The LCB method does make an adjustment to the HTL for the expected effect of noise exposure at 8 kHz, but the adjustment is typically small (about 6 dB in the above example, from 40 to 34 dB HL). Also, the LCB method is based on the assumption that the greatest NIHL typically occurs at 4 kHz; the adjustment of the HTL at 8 kHz is based on the threshold elevation at 4 kHz. Next, evidence is presented showing that the assumptions underlying the CLB and LCB methods do not hold for the types of noise exposures that occur during military service. Hereafter, NIHL occurring during military service is denoted M-NIHL.

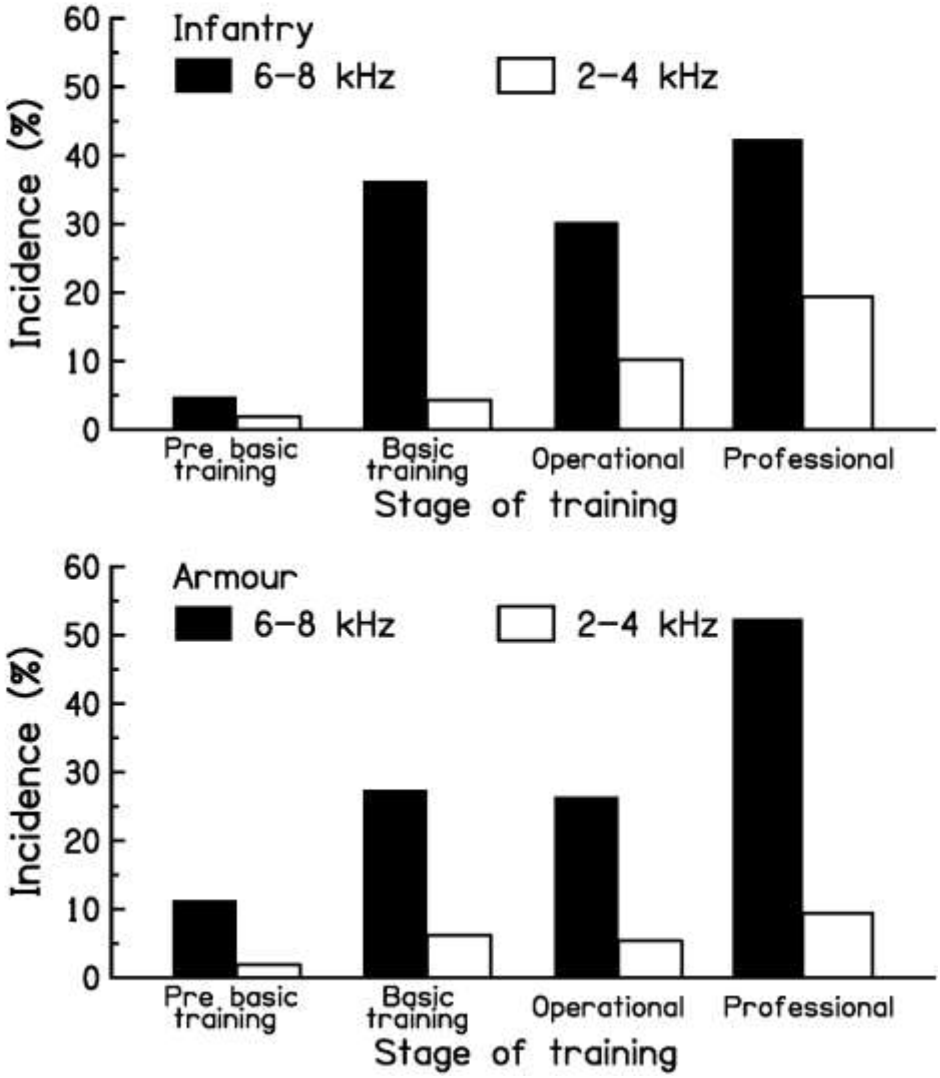

FIG. 1. Incidence of hearing loss in two frequency ranges (6-8 kHz, filled bars, and 2-4 kHz, open bars) for two types of military personnel (Infantry and Armour) at four stages of training. The data are from Attias *et al.* (2004). The duration of military service, and hence the total noise exposure, increased progressively across groups from left to right in the figure. There was no military noise exposure for the group “Pre basic training”. The group “Operational” had served three years of mandatory military service, while the group “Professional” had chosen to continue military service after the mandatory period of three years.

Figure 1 shows the prevalence of hearing loss (HTL > 20 dB HL) in 4000 military personnel for two frequency ranges, 6-8 kHz and 2-4 kHz and for two types of military personnel. It is obvious that prevalence is much higher for the frequency range 6-8 kHz than for the range 2-4 kHz. This is quite different from the pattern seen for noise-exposed factory workers (Passchier-Vermeer, 1974; Smoorenburg, 1992).

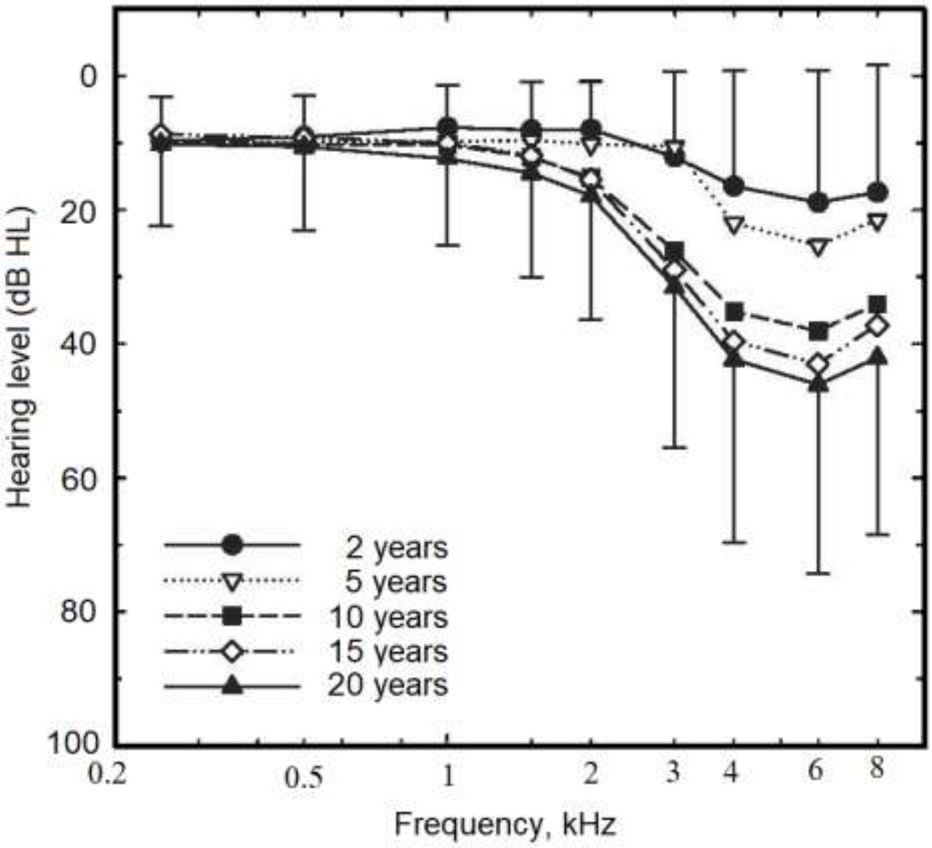

FIG. 2. Mean HTLs for the left ear (usually the worse-hearing ear) of over 3000 infantry personnel. Each curve is for one length of service, as indicated in the key. Error bars show one standard deviation for the group with 2 years of service (pointing up) and one standard deviation for the group with 20 years of service (pointing down). The figure is redrawn from Humes *et al.* (2006). The original data are from Walden *et al.* (1975).

Figure 2 shows mean HTLs for the left ear (usually the worse-hearing ear) of over 3000 infantry personnel. Each curve is for one length of service. The greatest mean hearing loss occurs at 6 kHz, and there is clear hearing loss at 8 kHz for the greater lengths of service. The mean hearing loss at 8 kHz is comparable to that at 4 kHz for each length of service.

It should be noted that the effects of stage of training (Fig. 1) and of length of service (Fig. 2) are potentially confounded with the effect of increasing age. However, Walden *et al.* (1975) stated that “the typical soldier in the present investigation entered active duty in his early 20s” and “very little of the hearing loss revealed in this investigation can be attributed to aging”. For example, for a man aged 43 years, based on age alone, the median audiometric threshold at 8 kHz (9 dB HL) is only 3 dB higher than the median audiometric threshold at 4 kHz (6 dB HL) (ISO 7029, 2017). Hence it can be concluded that the patterns shown in Figs. 1 and 2 can be attributed primarily to noise exposure rather than to age.

Figure 3 shows the percentage of ears of about 700 army officers having hearing loss at each of the audiometric frequencies for four different degrees of hearing loss. The percentage of ears showing hearing loss is greatest at 6 kHz and is generally second greatest at 8 kHz.

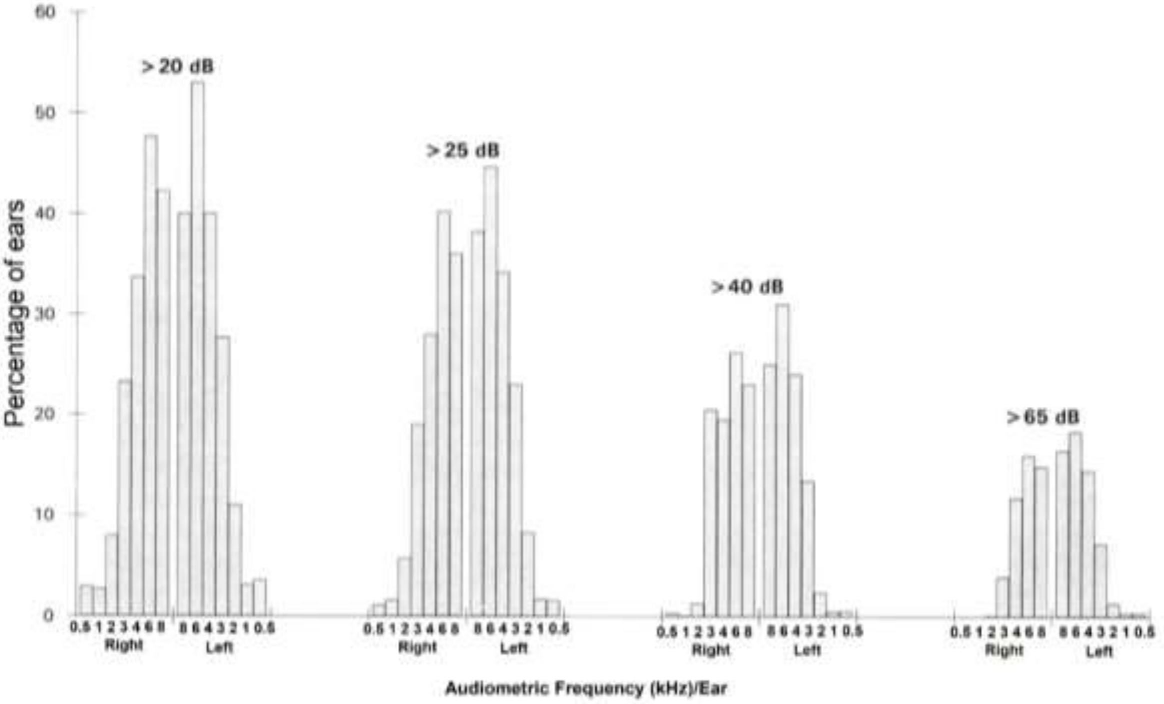

Fig. 3. The percentage of ears of army officers showing hearing loss at each audiometric frequency for four different degrees of hearing loss. The figure is redrawn from Ylikoski and Ylikoski (1994).

Xiong *et al.* (2014) compared the HTLs of two groups, each containing 109 men. Group I comprised military veterans with HTLs ≤20 dB HL at the end of the 1979 Sino-Vietnamese war, but most with hearing loss at the time of testing, about 30 years later. All had been exposed to the sounds of shooting without hearing protection. Group II were men with no military experience randomly chosen from a health examination centre in a military hospital. The two groups were matched in age. Mean HTLs for the two groups, and differences across groups, are shown in Table III. The military noise-exposed group showed greater hearing loss at 8 than at 4 or 6 kHz, and their hearing loss relative to the control group was greater at 6 and 8 kHz than at 4 kHz.

Table III. Mean HTLs obtained by Xiong *et al.* (2014) for a military noise-exposed group and a non-exposed group. The bottom row shows the difference in HTLs between the two groups at each frequency. Note that the differences are largest at 6 and 8 kHz.

	Frequency, kHz					
	0.5	1	2	4	6	8
Military exposed, dB HL	20.3	22.3	19.5	28.4	37.7	45.9
Non-exposed, dB HL	21.6	23.6	22.4	23.7	22.5	25.1
Difference, dB	–1.3	–1.3	–2.9	4.4	15.2	20.8

In summary, military noise exposure on average leads to hearing losses that are greatest at 4, 6 and 8 kHz, and the mean loss at 8 kHz is similar to or greater than that at 4 kHz. The CLB and LCB methods are based on the assumption that noise exposure has greater effects at 4 kHz than at 8 kHz. Hence, the CLB method may fail to diagnose M-NIHL when M-NIHL is actually present, and the magnitude of M-NIHL derived using the LCB method will be an under-estimate of the true M-NIHL.

IV. ANALYSIS OF AUDIOGRAMS OF NOISE-EXPOSED VETERANS

In this section, an analysis is presented of the characteristics of the audiograms of each ear of 58 military veterans who had claimed or were in the process of claiming compensation for NIHL that they alleged occurred during military service.

A. Characteristics of the study population

The study population was composed entirely of males. They had served in the British military (mostly the army, but some in the navy and air force) for between 4 and 20 years. Their ages at the times when the audiograms were obtained, usually just after the end of military service but sometimes up to 15 years afterwards, were between 29 and 60 years, with a mean of 45 years and a standard deviation (SD) of 8 years. All reported exposure to intense impact sounds from sources such as rifles (usually their own, fired from the right shoulder), mortars, explosions, grenades, and shoulder-mounted anti-tank weapons, including exposure without hearing protection (usually when it was necessary to hear orders). Many also reported exposure to more steady intense noise, for example the sound of helicopters. Occupational audiograms showed that at the start of military service all had HTLs within the normal range (thresholds ≤20 dB HL) for frequencies up to 6 kHz (often, there was no assessment of the HTL at 8 kHz). Most had hearing loss in both ears, but some had near-normal hearing in one ear (usually the right); this is described in more detail in section IV.B.

B. Characteristics of the audiograms

The audiograms were analysed only for frequencies from 1 to 8 kHz, since these are the frequencies that are relevant for the diagnosis and quantification of M-NIHL. All audiograms were obtained using the procedure recommended by the British Society of Audiology (2011). In some cases, the audiogram measurements had been repeated two or three times within a period of one year. In those cases, the average across all of the audiograms was taken.

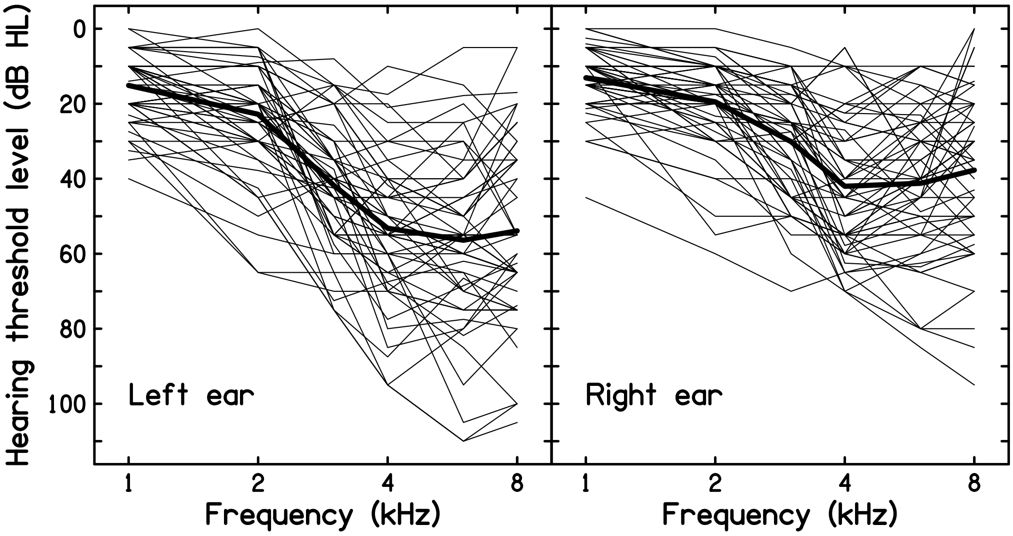

FIG. 4. Individual (thin lines) and mean (thick lines) HTLs for the left and right ears of the study population.

Figure 4 shows the individual (thin lines) and mean (thick lines) audiograms separately for the left and right ears. It is clear that there was large individual variability, both in the magnitude of the HTLs and in the shapes of the audiograms. A repeated-measures analysis of variance was conducted on the HTLs with factors ear and test frequency. There was a significant effect of ear: the mean HTL was significantly higher for the left than for the right ear; $F(1, 57) = 24.6$, $p < 0.001$, partial $\eta^2 = 0.301$. There was a significant effect of frequency: $F(5, 285) = 115.0$, $p < 0.001$, partial $\eta^2 = 0.669$. There was a significant interaction of ear and frequency: $F(5, 285) = 10.2$, $p < 0.001$, partial $\eta^2 = 0.152$. Post hoc tests with Bonferroni correction showed that HTLs did not differ significantly across the two ears for the frequencies of 1 and 2 kHz, but the thresholds were significantly higher for the left than for the right ear for all other frequencies ($p < 0.01$). In other words, the difference across ears was greatest for the frequencies where the HTLs were highest. The mean HTLs for the left (worse) ears show a similar pattern to that obtained by Walden *et al.* (1975), as shown in Fig. 2.

The difference across ears is consistent with previous findings (Themann and Masterson, 2019). It probably happens for two reasons. Firstly for people who fire shoulder-mounted weapons, when aiming the weapon, the head of the operator is tilted so that the right ear is partly shielded by the head from the sound emitted by the muzzle, while the left ear is facing more towards the muzzle. Secondly, communication signals are usually delivered via the left ear, so this ear is more often used without hearing protection. Hence, for military personnel, greater hearing loss for the left than for the right ear can be taken as supporting evidence that M-NIHL is present. However, some weapons systems fitted with suppression devices produce higher levels at the right ear than the left ear (Lobarinas *et al.*, 2016), so M-NIHL should not always be greater for the left ear. Indeed, there were two cases in the data set where HTLs were higher for the right than for the left ear.

It is noteworthy that while most ears had reasonably good hearing at 1 kHz, HTLs as high as 45 dB did occur. This is consistent with the idea that high intensity impact sounds can produce hearing loss over a wide frequency range, including 1 kHz (Ward and Glorig, 1961; Henderson and Hamernik, 1986), and even 0.5 kHz (Moon *et al.*, 2011).

As one measure of the variability in the shapes of the audiograms, the frequency or frequencies at which the HTL was highest was determined for each ear of each audiogram. If a single frequency had the highest HTL, that frequency was assigned a value of 1. If two frequencies shared the highest HTL, each frequency was assigned a value of 0.5. If three frequencies shared the highest HTL, each frequency was assigned a value of 0.33. For ease of interpretation, the values summed across all cases were expressed as percentages. The results are shown in Table IV. For the right ears, which had the smaller overall hearing losses, the highest HTL occurred most often at 4 kHz, which is similar to the pattern typically found for non-military NIHL (Passchier-Vermeer, 1974; Smoorenburg, 1992). However, for the left ears, which had larger overall hearing losses, the frequency at which the greatest hearing loss occurred was distributed more evenly across 4, 6 and 8 kHz. For the left ears, R3 of the CLB diagnostic method would often not be met, despite the greater overall hearing losses of the left ears.

Table IV. Percentage of cases where the highest HTL occurred for each ear and each frequency.

	Frequency, kHz				
Ear	2	3	4	6	8
Left	2	7	23	32	36
Right	2	4	49	21	24

V. PROPOSED METHOD FOR DIAGNOSIS OF M-NIHL

In what follows, it is assumed that it has been established that sufficient noise exposure has occurred (called here requirement R0). Evidence that military noise exposure is typically sufficient to cause hearing loss in a substantial proportion of men is provided by Fig. 1, showing that about 50 percent of professional military personnel have hearing loss in the frequency range 6-8 kHz, and by Fig. 2, showing that the mean hearing loss after 10 years of military service is greater than 30 dB at 4, 6, and 8 kHz. Consistent with this, Jokel *et al.* (2019) state that “All military personnel are going to be exposed to loud sounds. In fact, they are likely to have exposure to some of the most intense sounds that can be found in any occupation”. Also, Moon *et al.* (2011) showed that a single practice session on a rifle range without hearing protection was sufficient to cause hearing loss in some individuals.

The characteristics of M-NIHL are often similar to those of age-related hearing loss (presbycusis). About 20% of the ears in the study population had HTLs that increased progressively with increasing frequency. This makes a definite diagnosis of M-NIHL difficult for a person aged over about 40 years. However, in some (but not all) cases it is possible to distinguish M-NIHL from presbycusis, based on the observation that, in cases of presbycusis, the hearing loss is typically greater at 8 kHz than at 3, 4 or 6 kHz. For men not suffering from noise exposure, the difference between the HTLs at 8 and 6 kHz is about 1 dB at 40 years, increasing to about 9 dB at age 70 years (ISO 7029, 2017). The difference between the HTLs at 8 and 4 kHz is about 2 dB at age 40 years, increasing to about 17 dB at age 70 years. The difference between the HTLs at 8 and 3 kHz is about 3 dB at age 40 years, increasing to about 23 dB at age 70 years. In contrast, as described above, M-NIHL is typically greater at 6 than at 8 kHz and is typically similar at 4 and 8 kHz. Also, the maximum hearing loss sometimes falls at 3 kHz. Hence, a diagnosis of M-NIHL can be made if the following requirements are satisfied:

(R1) A single value of the HTL at 3, 4, 6, or 8 kHz is at least 10 dB higher than the HTL at 1 or 2 kHz. This is similar to requirement R1 of the CLB method, except that the frequencies “3, 4, or 6 kHz” have been replaced by “3, 4, 6, or 8 kHz” to allow for the findings summarized above, that military noise exposure typically produces the greatest hearing losses at 4, 6, and 8 kHz, but that it sometimes produces the greatest loss at 3 kHz.

(R2a) The difference between HTLs at 8 and 6 kHz is at least 5 dB smaller than would be expected from age alone or the difference between HTLs at 8 and 4 kHz or between 8 and 3 kHz is at least 10 dB smaller than would be expected from age alone, based on ISO 7029 (2017). For example, at 4 kHz R2a is satisfied if

$$[\mathrm{HTL}(8) - \mathrm{HTL}(4) + 10] \leq [\mathrm{AAHL}(8) - \mathrm{AAHL}(4)], \qquad \text{(Eq. 1)}$$

where HTL(x) is the HTL at frequency x (kHz) and AAHL(x) is the AAHL at frequency x (kHz). This is conceptually similar to requirement R3 of the CLB method, based on the presence of a notch or bulge in the audiogram, but is based on the evidence reviewed above indicating that military noise exposure typically leads to less hearing loss at 8 than at 6 kHz, and to similar hearing loss at 4 and 8 kHz, and sometimes leads to the greatest hearing loss at 3 kHz, whereas age alone typically leads to greater hearing loss at 8 than at 3, 4 or 6 kHz.

If requirements R1 and R2a are met, this provides reasonably strong evidence for M-NIHL. If requirement R2a is not met, this does not imply the absence of M-NIHL, since military noise exposure can have a substantial effect, and sometimes its maximal effect, on the HTL at 8 kHz. If requirement R2a is not met, then a diagnosis of M-NIHL can be made if R1 is met, there is no reason to suspect a hearing loss that is not age-related or noise-related, and the following requirement is met:

(R2b) The HTL at any one of 4, 6, or 8 kHz is at least 20 dB higher than the median HTL for each frequency expected for that age, based on ISO 7029 (2017).

Table V shows the results of this diagnostic method for the hypothetical case of a man who had served in the army for 10 years, based on the curve for that length of service in Fig. 2. An age of 28 years was assumed. R1 and R2a are both met, so the diagnosis of M-NIHL is positive.

Table V. Application of the diagnostic method to a hypothetical case.

Age	28						
Frequency, kHz		1	2	3	4	6	8
Hearing threshold level, dB HL		10	15	26	35	39	34
Age-associated hearing loss (AAHL), dB HL		0.2	0.4	0.6	0.7	0.9	1.1
Requirement R1 met?				TRUE	TRUE	TRUE	TRUE
RequirementR2a met?				FALSE	FALSE	TRUE	
Requirement R2b met?					TRUE	TRUE	TRUE

Table VI shows the application of the method to the same hypothetical case, except that the HTL at 6 kHz has been decreased by 2 dB, a small amount given the typical accuracy of HTLs, which are usually measured to the nearest 5 dB and for which the standard deviation of repeated measurements is about 6 dB for frequencies of 6 and 8 kHz (Flamme *et al.*, 2014). In this case, R1 is still met, but R2a is not met. However, R2b is met, so a diagnosis of M-NIHL is made, albeit with less confidence than for the case in Table V.

Table VI. Application of the diagnostic method to the same case as in Table V, but with the HTL at 6 kHz decreased by 2 dB.

Age	28						
Frequency, kHz		1	2	3	4	6	8
Hearing threshold level, dB HL		10	15	26	35	37	34
Age-associated hearing loss (AAHL), dB HL		0.2	0.4	0.6	0.7	0.9	1.1
Requirement R1 met?				TRUE	TRUE	TRUE	TRUE
RequirementR2a met?				FALSE	FALSE	FALSE	
Requirement R2b met?					TRUE	TRUE	TRUE

VI. APPLICATION OF THE DIAGNOSTIC METHOD TO THE STUDY POPULATION

The diagnostic method described above was evaluated using the sample of 58 audiograms (116 ears) described in section IV. The requirements of the CLB method are denoted R1(CLB) and R3(CLB), while the requirements of the new method are denoted R1(BM), R2a(BM) and R2b(BM). Requirements R1(CLB) and R1(BM) were met in all cases.

For the right ears, R3(CLB) was met in 39 cases, while either R2a(BM) or R2b(BM) or both were met in 55 cases. Thus, a positive diagnosis of M-NIHL was made in more cases for the new method. For all cases where R3(CLB) was met, either R2a(BM) or R2b(BM) or both were met. Thus, the new method did not fail to diagnose any cases that were positively diagnosed using the LCB method. For the 3 cases where neither R2a(BM) or R2b(BM) were met, the audiograms were near-normal, while the left ears had greater hearing losses. Of the 19 ears for which R3(CLB) was not met, R2a(BM) was met in 3 cases and R2b(BM) was met in 15 cases.

For the left ears, R3(CLB) was met in 41 cases, while either R2a(BM) or R2b(BM) or both were met in 57 cases. Thus, again a positive diagnosis of M-NIHL was made in more cases for the new method. For all cases where R3(CLB) was met, either R2a(BM) or R2b(BM) or both were met. For the one case where neither R2a(BM) nor R2b(BM) were met, the audiogram was near-normal, while the right ear had greater hearing loss. Of the 19 ears for which R3(CLB) was not met, R2a(BM) was met in 2 cases and R2b(BM) was met in 18 cases.

There were ten cases for which R3(CLB) was met for one ear, but not for the other ear, when the ear that failed to meet R3(CLB) had greater hearing loss overall. It seems likely that the worse-hearing ears did have M-NIHL, but that R3(CLB) was not met because the HTL at 8 kHz was markedly elevated. For all such cases, M-NIHL was diagnosed for both ears using the new method.

It seems likely that the great majority of the study population had M-NIHL in at least one ear, given their normal audiograms at the start of military service, their high unprotected noise exposure, and a hearing loss at high frequencies that was greater than expected for their age in at least one ear. The present analysis suggests that the new method gives more accurate diagnosis of M-NIHL than the CLB method.

VII. METHOD FOR QUANTIFICATION OF M-NIHL

M-NIHL can be quantified by comparing the measured HTLs with the thresholds expected from age alone, based on published standards such as ISO 7029 (2017), or on other normative data (Flamme *et al.*, 2020). This method is appropriate provided that there is no evidence for a cause of hearing loss other than age and noise exposure. Some medical experts use this method to quantify all types of NIHL. The ISO standard specifies the distribution of HTLs for each age and each audiometric frequency. For quantification of M-NIHL, it is necessary to select an appropriate percentile for the individual concerned. For military personnel, it will often be possible to select the appropriate percentile based on audiograms obtained close to the start of military service. However, occupational audiograms are usually obtained under unknown conditions, and their validity is questionable.

Another possibility is to select the percentile so that the AAHL at 0.5 kHz matches the measured HTL for the ear with the better HTL at 0.5 kHz. This is based on the assumption that military noise exposure has little effect on the HTL at 0.5 kHz, consistent with the data in Fig. 2. However, there are some problems with this approach. Firstly, military noise exposure can produce NIHL for some individuals at 0.5 kHz (Moon *et al.*, 2011). Secondly, a small error in the measured HTL at 0.5 kHz might result in the choice of an extreme percentile and an inaccurate estimate of AAHL at high frequencies. Also, the audiometric threshold at 0.5 kHz might be affected by noise in the test environment. If occupational audiograms are not available, or are deemed to be too unreliable, then the best approach may be to use the 50th percentile.

Table VII shows the application of the quantification method to the same case as in Table II. Note that the AAHL values in Table VII differ from those in Table II, because the

LCB method is not based on ISO 7029 (2017), but is based on a modified version of an earlier ISO standard. To make the AAHL values similar to those in Table II, the age was still taken as 50 years, but the percentile was chosen as the 30th.

Table VII. Application of the quantification method to the same case as in Table II.

Age, years	50						
Percentile	30						
Frequency, kHz		1.0	2	3	4	6	8
Hearing threshold level, dB HL		10	10	15	45	45	40
Age-associated hearing loss (AAHL), dB HL		7.6	11.6	14.9	17.9	22.5	26.0
Estimated noise-induced hearing loss (NIHL), dB		2.4	-1.6	0.1	27.1	22.5	14.0
Set NIHL to 0 if NIHL < 0		2.4	0.0	0.1	27.1	22.5	14.0
Mean M-NIHL at 1, 2 and 3 kHz, dB	0.8						
Mean M-NIHL at 1, 2 and 4 kHz, dB	9.9						

The estimated M-NIHL is slightly larger than for the LCB method. The estimated NIHL is 0.8 dB (versus 0.7 dB in Table II) when averaged across 1, 2, and 3 kHz, and 9.9 dB (versus 7.3 dB in Table II) when averaged over 1, 2, and 4 kHz.

VI. OTHER CONSIDERATIONS

A. Asymmetric hearing loss

As noted earlier, it is often the case that hearing loss is greater for the left ear than for the right ear (Themann and Masterson, 2019), and this was the case for the sample examined in this paper. An example of the application of the diagnostic method is shown in Table VIII for the right ear and Table IX for the left ear. This 36 year old man had served 10 years in the army. The HTLs were averaged across several audiograms obtained within a short time period, which is why they are not given to the nearest 5 dB.

Table VIII. Results of the diagnostic method for the right ear of a man aged 36 years.

Male							
Age, years	36						
Frequency, kHz		1	2	3	4	6	8
Hearing threshold level, dB HL		10.0	12.5	7.5	7.5	47.0	40.0
Age-associated hearing loss (AAHL), dB HL		0.9	1.6	2.3	2.8	3.6	4.2
Requirement R1 met?				FALSE	FALSE	TRUE	TRUE
RequirementR2a met?				FALSE	FALSE	TRUE	
Requirement R2b met?					FALSE	TRUE	TRUE

Table IX. Results of the diagnostic method for the left ear of a man aged 36 years.

Male							
Age, years	36						
Frequency, kHz		1	2	3	4	6	8
Hearing threshold level, dB HL		7.5	5.0	10.0	27.5	57.0	70.0
Age-associated hearing loss (AAHL), dB HL		0.9	1.6	2.3	2.8	3.6	4.2
Requirement R1 met?				FALSE	TRUE	TRUE	TRUE
RequirementR2a met?				FALSE	FALSE	FALSE	
Requirement R2b met?					TRUE	TRUE	TRUE

For the right ear, requirements R1 and R2a are met, supporting a diagnosis of M-NIHL. For the left ear, R1 is met but R2a is not met. However R2b is met. Overall, the results support a diagnosis of M-NIHL. The results for the left ear illustrate how greater noise exposure can lead to considerable hearing loss at 8 kHz and the absence of a bulge or notch. The left ear would not satisfy requirement R3 of the CLB method, whereas the right ear would, despite the fact that the hearing loss at 4, 6 and 8 kHz is greater for the left than for the right ear.

B. The importance of hearing at high frequencies for the intelligibility of speech in noise

Compensation for occupational NIHL is usually based on the mean estimated NIHL at 1, 2 and 3 kHz in the UK (King *et al.*, 1992) and the mean across 0.5, 1, 2 and 3 kHz in the USA (American Medical Association, 2008; Dobie, 2011). This is based on the implicit assumption that hearing loss for frequencies above 3 kHz has no material adverse consequences. In the author’s opinion, this assumption is incorrect; for a review, see Moore (2016). In any case, given that a primary complaint of people with hearing loss is difficulty understanding speech in noise (Plomp, 1978; Moore, 1996), the important issue is: what are the most important audiometric frequencies for predicting the ability to understand speech, especially in noisy situations?

Kryter *et al.* (1962) studied the relationship between the results of a variety of speech tests and the characteristics of the audiogram, for participants with a wide range of audiometric configurations. They found that “the ability to perceive speech can be predicted as well by the hearing thresholds at 2000, 3000, and 4000 cps alone as it can by including the losses at all the other frequencies tested” and concluded that “the three most important test frequencies to use for predicting the ability to understand speech would be 2000, 3000, and 4000 cps.”

Smoorenburg (1992) published a large-scale study of the effects of NIHL on the ability to understand speech in noise and of the relationship of that ability to the audiogram. He measured the speech reception threshold (SRT) at which 50% of sentences in noise could be understood. He found that the best predictor of the SRT was the average of the HTLs at 2 and 4 kHz (denoted $PTA_{2,4}$). Smoorenburg also examined which single HTL (i.e. which single frequency) gave the most accurate prediction of the SRT. He found that the HTL at 4 kHz gave the most accurate prediction, although HTLs at 3 and 6 kHz gave predictions that were nearly as accurate. These findings clearly indicate that the hearing loss at high frequencies (2-6 kHz) is the best predictor of the intelligibility of speech in noise for people with NIHL.

The findings of Smoorenburg (1992) were based on participants who worked in noisy factories. However, similar results have been found for military personnel. Wilson (2011) tested 3266 veterans, many of whom had been exposed to intense noise. The intelligibility of speech in noise was assessed using the Words-in-Noise (WIN) test, which evaluates word recognition in multi-talker babble at seven signal-to-noise ratios (SNRs) and uses the 50% correct point (in dB SNR) as the primary outcome metric. Wilson found that scores on the WIN were predicted significantly better by the average HTL at 1, 2 and 4 kHz than by the average HTL at 0.5, 1, and 2 kHz, confirming the importance of high-frequency hearing for the ability to understand speech in noise.

Given these findings, the audiometric frequencies used to assess the severity of hearing loss and to award damages should include 4 kHz. Given that lower frequencies contribute to the ability to understand low-level speech in quiet (Smoorenburg, 1992), a reasonable compromise is to use the average across 1, 2 and 4 kHz to assess severity.

VII. DISCUSSION

The differences between M-NIHL and NIHL produced by exposure to broadband noise in factories can probably be accounted for by the differences in the characteristics of the noise. The typical 4-kHz notch associated with long-term exposure to broadband factory noise can be explained in the following way. The ear canal produces an acoustic resonance that boosts the sound level at the eardrum (relative to that measured with a microphone placed at the center of the position of the listener’s head) by about 15 dB for frequencies close to 3 kHz (Shaw, 1974). Hence, the level of a broadband sound at the eardrum is greater for frequencies close to 3 kHz than for lower or higher frequencies (Murphy *et al.*, 2015). The characteristic frequency (CF) of a given place within the cochlea depends on sound level (Ruggero, 1992; McFadden, 1986; Moore *et al.*, 2002). The place with a CF of 4 kHz at low sound levels responds most strongly to frequencies close to 3 kHz at levels of 90-100 dB SPL. Because of these two effects, exposure to a moderately intense broadband noise produces maximum damage at a place whose CF at low levels is close to 4 kHz, and it is this damage that is measured in the audiogram. The effect on the audiogram is probably mediated mainly by loss of outer hair cell function, which leads to reduced effectiveness of the active mechanism in the cochlea (Borg *et al.*, 1995).

The situation is very different for the types of impulsive sounds that military personnel are exposed to. Firstly, the level-dependent shift in CF may be greater than for factory noises because of the higher sound levels, leading to maximum damage for higher frequencies. Secondly, the high peak levels may damage the cochlea by causing rapid mechanical failure and injury (Henderson and Hamernik, 1986). Also, the acoustic reflex does not protect the cochlea from isolated high-intensity impulses (Price, 2007). Hence, high-intensity impulses can lead to “acoustic trauma”, which can affect hearing over a wide frequency range (Ward and Glorig, 1961). For a review, see Humes *et al.* (2006).

It is also possible that the frequency at which the greatest hearing loss occurs tends to shift towards higher frequencies with increasing severity of the loss. This is not consistent with the data for military noise exposure shown in Fig. 2, since on average the greatest loss occurred at 6 kHz regardless of the severity of hearing loss (which co-varied with length of service). However, it is consistent with the present analysis of the 58 audiograms for noise-exposed military personnel; for the right ears the highest HTL occurred most often at 4 kHz, while for the left ears, which on average had greater hearing losses, the highest HTL occurred more often at 6 and 8 kHz (Table IV).

It should be noted that the perceptual consequences of sensorineural hearing loss, including NIHL, involve much more than reduced audibility. Other factors include reduced frequency selectivity (Pick *et al.*, 1977), reduced sensitivity to temporal fine structure (Hopkins and Moore, 2007), and reduced binaural processing abilities (Füllgrabe and Moore, 2018). In addition, the high levels of sounds encountered in military service are more likely to lead to cochlear synaptopathy than the more moderate levels encountered in factories (Valero *et al.*, 2017). This cochlear synaptopathy may contribute to difficulty in understanding speech in background sounds (Liberman *et al.*, 2016), although this is controversial (Bramhall *et al.*, 2019).

IX. CONCLUSIONS

Exposure to noises of the type that are encountered in military service typically leads to hearing loss that is greater at 6 kHz than at 4 kHz and is similar at 4 and 8 kHz. This makes it inappropriate to diagnose and quantify M-NIHL using methods that depend on a notch or bulge in the audiogram at 4 kHz. This paper has proposed methods for diagnosing and quantifying M-NIHL. Three requirements are specified for diagnosing M-NIHL. Quantification of M-NIHL is done by comparison with HTLs for non-noise exposed individuals, as specified in ISO7029 (2017).

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