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IN-DEPTH REVIEW

Noise-induced hearing loss and hearing conservation in mining

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Background Noise exposure is prevalent in mining, and as the prevalence of noise-induced hearing loss has not changed much in the past two decades, hearing conservation is an important issue.

Objectives To review the literature and highlight important developments in the field.

Methods A review of the literature using OVID as the primary search engine, using the search terms as: noise, occupational; hearing loss, noise induced; ear protective devices; and mining.

Results A total of 66 articles were found, but only 11 were in the English language and few were published in the past 10 years. This is disappointing, because neither noise exposure nor the consequent risk of noise-induced hearing loss seems to have changed much in the past 20 years. Noise is, however, a generic hazard, and this article reviews current best practice in prevention.

Key words Hearing conservation; mining; noise-induced hearing loss; occupational noise.

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Introduction

Mining minerals has always been an arduous forceful task, both underground and on the surface. Rosen [1] quotes Diodorus Siculus: 'Of those that who are condemned to this disastrous life such as excel in strength of body pound the shining rock with iron hammers, applying not skill but sheer force to the work, and they drive galleries, though not in a straight line, but in the direction taken naturally by the glistening stone'. This situation persisted throughout much of history: although coal ushered in the industrial revolution and most of industry was mechanized by energy derived from it, mechanization in mining itself was slow in coming so that, even in the twenties, mining was regarded as 'a pick and shovel proposition'[2]. Noise is now, however, a generic hazard common to all commodities and, to a greater or lesser extent, all operations within mining.

There are other hazards in mining that overshadow noise exposure as a cause of mortality and morbidity, in particular accidents and mines dust. This is perhaps why, outside of Eastern Europe, there has been little published research activity in the past decade or so. This is disappointing in view of the fact that, in the USA, the National Institute for Occupational Safety and Health (NIOSH) is of the opinion that 'Overexposure to noise remains a widespread, serious health hazard in the U.S. mining industries despite 25 years of regulation'[3]. There is, however, hope for the future: NIOSH has eight current research projects that are investigating the problem of hearing conservation in the industry [3,4].

Noise exposure sources

NIOSH estimates that 80% of US miners go to work in an environment where the time-weighted average (TWA) exceeds 85 dB, and that 25% of these are exposed to a TWA noise level that exceeds 90 dB [3]. Estimates of the noise exposure from plant and equipment are shown in Table 1 [5]. One of the first mining operations to become mechanized was that of boring shot-holes, and the pneumatic percussion drill is still the major noise hazard

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Table 1. Estimates of noise exposure from plant and equipment

Noise source	Range (dB)	Mid point
Cutting machines	83–93	88
Locomotives (electrical)	85–95	90
Haulage truck	90–100	95
Loaders	95–100	98
Long-wall shearers	96–101	99
Chain conveyors	97–100	99
Continuous miners	97–103	100
Loader-dumper	97–102	100
Fans	90–110	100
Pneumatic percussion tools	114–120	117

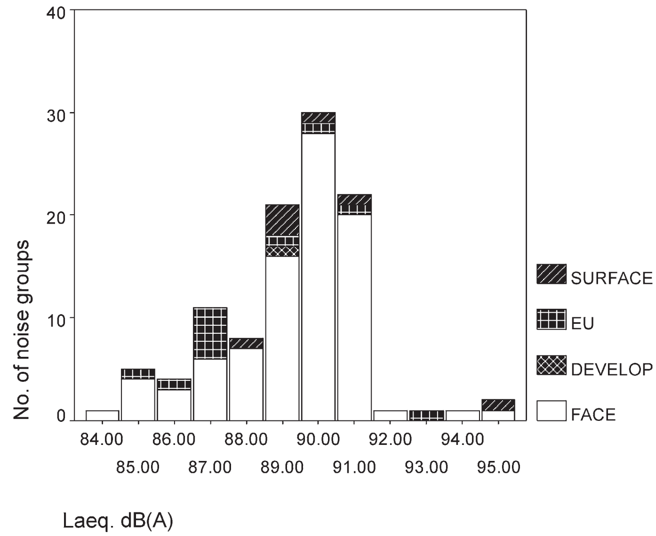

Figure 1. Estimated 8 h L_{aeqs} for coal mining in the UK.

in mining today. Impact from the drill bit, mechanical vibration from the drill casing and impulse noise from the exhaust generate the noise. The equipment may be either hand held ('jigger-picks' in the UK) and used in the maintenance of roadways to keep them open by 'dinting' the floor or 'ripping' the roof, or man-handleable, such as the drills used for placing roof-bolts. Machine-mounted percussion drills may also be used in development work.

Ancillary equipment is also noisy: this includes fans and blowers for mines ventilation, where the noise comes from structural resonance and energy from the aero-dynamic flow.

The extractive equipment itself, either continuous miners or longwall shearers, produce continuous noise from the power pack and transmission (gear) system and impact noise from the cutting head and the associated armoured conveyor system.

Transport and mechanical handling noise comes from diesel powered load handlers and materials or man carrying haulage equipment. The noise sources are engine, transmission and exhaust, while diesel powered locomotives and man-riding cars have additional components from wheel-track impulse noise and structural vibration. Conveyor systems, apart from the drives, should not be excessively noisy if properly maintained.

The table does not illustrate the likely levels of impulse noise from explosive charges and blasting, also prevalent in mining. Blasting underground differs from that on the surface, being influenced by mine geometry, openings and friction from wall roughness. As with other impulsive exposures, the cumulative effect on mine workers is unclear.

As with all 'grab' sampling, the levels so far illustrated do not mean that the eight hour equivalent exposures will necessarily be of the same magnitude, because some of the noisy tasks are not continuous. Figure 1 shows the 8 h equivalent continuous exposure ($L_{aeq(8h)}$) calculated from recorded levels and work activities in a British deep coal mine [6] in which 70% of the estimated exposures lay between 89 and 92 dB. A smaller personal dosimetry sample found levels that also lay within this range. These levels are less than the grab samples would suggest but still well in excess of the UK standards.

Prevalence and severity of noise-induced hearing loss in mining

There is no doubt that the majority of miners are exposed to hazardous levels of noise, most exceeding an $L_{aeq(8h)}$ of 85 dB, and some the peak exposure standard of 140 dB. Noise-induced hearing loss (NIHL) may therefore be prevalent. The diagnosis is essentially one of exclusion [7] and should be made on a history of sufficient noise exposure and consistent audiometric findings. A good noise exposure history requires careful assessment of all sources of noise, both occupational and non-occupational. Ideally, a standard audiometric questionnaire should be used [8] and the information should facilitate the calculation of a life-time noise dose. For mining jobs, it should be possible to calculate this based on the job title by looking at the contribution from individual tasks and activities. For other jobs and leisure exposure, it is important not only to note that exposure (for example to chainsaws or other powered tools) has taken place but to estimate the duration of exposure in terms of daily, weekly or monthly hours of use. It is especially important to document firearms exposure in terms of the weapon used and the number of rounds fired weekly, monthly or annually.

As regards audiometric standards, the first sign of NIHL is a small depression in the audiogram at 4 kHz that deepens and widens as the noise exposure continues, the audiometric 'notch' [9,10]. Detecting such a notch may make a qualitative judgement on the audiogram, but certain provisos need to be borne in mind because audiograms present complex patterns and 'shape' factors are important in notch recognition [11]. Notches may also be due to other causes, especially so with the 6 kHz notch that may be due to an incorrect audiometric standard at this frequency [12].

Another qualitative evaluation is to classify an individual as 'deaf' or 'not deaf', but the wide variability in the 'normal' value for threshold at any particular frequency means that any cut-off point will be somewhat arbitrary. However, the Health & Safety Executive recommends a useful hearing classification: this scheme classifies individuals in 'warning' or 'referral' categories if hearing levels at the average of the low (0.5, 1 and 2 kHz) or high (3, 4 and 6 kHz) audiometric frequencies exceeds criterion values (Table 2) [13]. Individual or group comparisons with normative values are also useful, and tables of the hearing levels to be expected in standard populations, either screened or unscreened for ear disease, are available [12,14]. The ISO 1999 [15] tables can also be used to predict the proportion of individuals who would exceed handicap or disability criteria.

Because of the different ways in which hearing loss is defined, it is difficult to get a clear picture of the prevalence of NIHL in mine workers. A study of 2484 white South African goldminers [16] defined social impairment as an average loss of >25 dB for the audiometric frequencies 0.5, 1 and 2 kHz. At age 58, 21.6% fell into this group, while reference to ISO 1999 [15] shows that only 5% of a non noise exposed group would be expected to have this level of disability.

A report on 665 British mine-workers [6] showed hearing losses roughly in accord with median noise exposures (~90 dB), but, taking handicap as exceeding a mean hearing level of 30 dB at 1, 2 and 3 kHz, fewer miners were observed ($n = 23$, 3.5%) than were predicted ($n = 45$, 6.7%) to reach handicap with this level of exposure. This does indicate the excess risk, because just nine individuals (1.3%) would reach handicap level in the absence of noise exposure. A recent NIOSH analysis of a large sample of audiograms [17] showed that at age 50, ~90% of coal miners and 49% of metal/non-metal miners had a hearing impairment. By contrast, only 10% of the non-occupational noise-exposed population had a hearing impairment at age 50.

Table 2. Health & Safety Executive Hearing Classification: sum of hearing levels

Age in years	0.5, 1and 2 kHz		3, 4 and 6 kHz	
	Warning level	Referral level	Warning level	Referral level
20–24	45	60	45	75
25–29	45	66	45	87
30–34	45	72	45	99
35–39	48	78	54	111
40–44	51	84	60	123
45–49	54	90	66	135
50–54	57	90	75	144
55–59	60	90	87	144
60–64	65	90	100	144
65+	70	90	115	144

Methods of controlling noise exposure in mining, including personal protection equipment

The principles of the 'hierarchy of control' [18] need to be examined carefully in mining, because noise elimination techniques have been evolving over the past few decades. Some of the development involves new materials and technology, such as isolated mountings for shearer bit blocks or quieter gear drives. Modified design will eliminate or reduce impact points on conveyor systems, and enable enclosure of noisy power packs or drives. Senior management need to be aware of these factors and adopt the principle of 'buying quiet'. Replacing worn components, especially in vibratory equipment, and having good maintenance schedules may also dramatically reduce noise.

Some of the changes involve both new technology and changed working practices; for example, the development of tele-controls for pneumatic percussion drills have allowed the separation of man and machine [19].

Hearing protective devices (HPDs) are often used, and misused, in the mining environment. The danger is that the protection factor of hearing protection degrades very rapidly with poor compliance or ineffective fit [20], and so they often do not control the noise hazard. The compliance issues arise because HPDs are not particularly comfortable and interfere with communication, so if noise is intermittent—always a problem in mining—they are unlikely to be worn or may frequently be taken off. For the sake of comfort and communication it is therefore essential that the HPD is matched to both the individual and the noise environment in which they work: it is not sufficient to make a general issue of an HPD with a high protection factor.

An increased perception of risk may help compliance; for example, in agriculture, the intense noise from chainsaws may persuade individuals to wear HPDs [21]. The effect of an adequate warning of hazardous noise levels may therefore be a useful compliance aid, and current research is looking at the use of relatively inexpensive personal noise monitors [22]. Ear muffs are the best technical choice as they give better sound attenuation than ear plugs. Paradoxically, plugs seem to perform better, the explanation being that if noise is intermittent, it is considerably easier to remove muffs than plugs [23]. They may therefore be a better option in mining work.

An adequate HPD programme must therefore encompass noise hazard evaluation, selection of the most appropriate HPD device, education and training in their use, adequate maintenance and ongoing monitoring of hearing.

Audiometry

Because of the high noise levels found and the widespread use of hearing protection as a control measure, it is essential to detect incipient NIHL, and audiometric testing should be carried out. The first step in this is to perform careful baseline audiometric testing in suitable environmental conditions [24]. Although automatic sweep-frequency (Bekesy) audiometry and, indeed, industrial audiometry in general sometimes gets a bad press, the levels found with the automatic technique are generally 2.5 dB hearing level (HL) better than manual pure tone audiometry [25].

The most essential role of audiometry in hearing conservation is the early detection of noise-induced hearing loss by way of a deterioration from 'base line' hearing status, the so called 'significant threshold shift' (STS) identified during serial audiometry.

There are two ways of doing this. The first is to do periodic audiometry in the standard way, after a period of quiet. This will detect a permanent threshold shift (PTS). The main problem is audiometric test–retest variability, which has a standard deviation of the test–retest difference (SD_{diff}) of between 3 and 10 dB HL [26]. At likely mining noise exposures of between 85 and 95 dBA, the PTS expected after 1 year would be 4–5 dB HL at the most noise-sensitive frequency, 4 kHz. The permanent loss is less than the typical test–retest variability and, of even more concern, is permanent by the time it is detected.

An alternative approach, and one that adheres more closely to the principles of early detection and prevention, is to identify the temporary hearing loss that occurs directly after noise exposure. This temporary threshold shift (TTS) is regarded as a precursor of a permanent loss, is larger and, according to Kryter *et al.* [27], is of the same order as the permanent loss expected after exposure to the same level of noise for 10–15 years. This shift is still not large, for example with exposures lying between 85 and 90 dBA TTS will be in the range 8–12 dB HTL for the 5% of the population most sensitive to the effects of noise. The challenge is therefore to find a value of TTS that indicates an STS, one likely to be due to noise.

Part of the solution is to choose a significant threshold shift criterion in terms of size, frequency or combination of frequencies that is valid [28]. However, there is no 'gold standard' for detecting occupational NIHL and any chosen criterion will be a compromise. A 15 dB shift in the threshold between tests at any frequency (the 'any frequency' STS criterion) increases the probability of a false positive quite markedly. The effect was shown in a study of engineering workers, which failed to find an association between 'any frequency' STS and noise exposure, this despite good audiometric repeatability (an SD_{diff} of 3–5 dB across the frequencies tested) that should have allowed the audiometry to detect TTS had it been present [29]. This is why NIOSH, in their 'Criteria for a recommended standard: occupational noise exposure' [30], have finally selected a '15 dB twice' criterion. This requires a confirmatory audiogram, carried out within 30 days of the initial test and after 12 h of quiet, to confirm whether the shift persists in the same ear at the same frequency. As an alternative to this an 'optional' immediate retest may be carried out that in most cases (as the criterion identifies) will demonstrate that the worker does *not* have a persistent threshold shift.

Practical problems, in terms of getting the mine worker to an audiometer before the TTS wears off, may also limit the utility of TTS audiometry in mining.

Newer audiological tests are being developed and these seem to hold promise by providing less variable responses [31]. Otoacoustic emissions (OAE) are a release of sound energy from the cochlea due to by-products in basilar membrane motion. They are transmitted by the cochlear fluids to the middle and external ear, where they are recorded as one of two main classes of output. Distortion product OAEs (DPOAEs) are generated by stimulating the ear with two continuous primary tones, the distortion product being a function of the difference between the tone frequencies. Transient evoked OAEs (TEOAEs) are evoked by stimulating the ear with a series of clicks. Unfortunately, neither of these tests can be used to predict auditory thresholds, as there is great variability between individuals, but they are stable over time and are sensitive to noise exposure, both types being diminished. The most promising mode of testing appears to be TEOAEs that have an SD_{diff} of 1–2 dB at click levels of 60–90 dB SPL centred on 3 and 4 kHz [31]. The methods are still evolving, and at present there is not enough experience with the techniques to recommend their use as an everyday tool.

So, although it has shortcomings, pure tone audiometry still has a place in hearing conservation. Although the utility of audiometry as applied to individuals is equivocal, the benefits may be enhanced by grouped analysis of audiometric results [32]. The sophistication of the method used will depend on the numbers of employees involved. Simple graphical methods, e.g. box-plots, can be used for relatively few employees, and more complex models, which examine the multifactorial nature of hearing loss, can be used as the population size increases. Knowledge of the hearing status of occupational groups is also necessary for safety, as the next section will show.

Determining fitness for duty in cases of hearing loss

Because of the many safety critical issues involved in mining, certain standards of auditory performance are necessary for mine-workers, specifically related to abilities in signal detection, signal localization and speech intelligibility [33].

The single most important fitness factor is whether or not an individual suffering from a hearing loss is capable of hearing and locating an auditory alarm or warning, for example conveyor pre-start signals and loader reversing alarms. The basic principles of signal detection theory are simple, and illustrated in Figure 2. The noise masks the signal, so the signal (or speech) must then be of sufficient intensity to overcome the masking effect, the 'masked pure tone threshold' that must be exceeded in order for the signal to be heard. If, in addition, the listener has a hearing loss, usually at high frequency because of presbycusis or noise-induced hearing loss, the signal must be of sufficient intensity to overcome that loss, the absolute threshold criteria. This gives a composite audibility criterion, and in practice this level must be exceeded by ~15 dB in order to gain attention, giving a minimum effective signal level.

The difficulty lies in correlating the ability to hear pure tones in the quiet (the audiometric test) with the ability to hear signals in noise, because in practice there is substantial variability in masked thresholds and the two are not well correlated. This means that masked thresholds must be obtained, representative of the hearing abilities of the population under study and taking into account the noise spectrum and acoustic conditions of the exposure. Models of hearing are available that allow input of these variables and subsequent prediction of the proportion of individuals who would be disadvantaged; however, they are complex and are really not clinical tools [33]. Despite that, they do allow effective signals to be designed, and this is a science in itself: although the signal must be audible and gain attention, it must not produce startle effects, interfere with other tasks or add to the noise dose.

Other aspects of mining depend on close teamwork, and person-to-person speech communication is important in tasks such as advancing the face, erecting supports and coordinating materials transfer. Indirect communications systems by telephone, tannoy or wireless are universal, and are essential to the smooth running of operations.

Understanding speech is more complex, being governed not only by audibility but by intelligibility, which incorporates aspects such as the context in which the message is delivered, vocabulary and dialect.

Any tools that take these factors into account must of necessity be even more complex than signal detection models; nevertheless, several have been developed over the years.

The first of these was the Articulation Index (AI), originally developed by French and Steinberg [34], and refined by Kryter [35,36]. The basic method uses the concept of an 'idealized speech spectrum' and the third octave spectrum levels of the background noise. If a particular background noise third octave spectrum level is above the corresponding idealized speech spectrum level, then the contribution to AI is zero. If the difference is positive then it will make a contribution. Each contribution is multiplied by a weighting factor specific to the particular third octave band. The sum of all the contributions is the AI value. The index varies from 0 to 1, representing the proportion of words that are likely to be heard. Values <0.4 indicate that speech communication difficulties are likely; values between 0.4 and 0.7 indicate that some difficulties are likely to occur; and values >0.7 indicate that almost perfect speech communication is possible. Figure 3 incorporates a threshold criterion for the population under study and shows the frequency

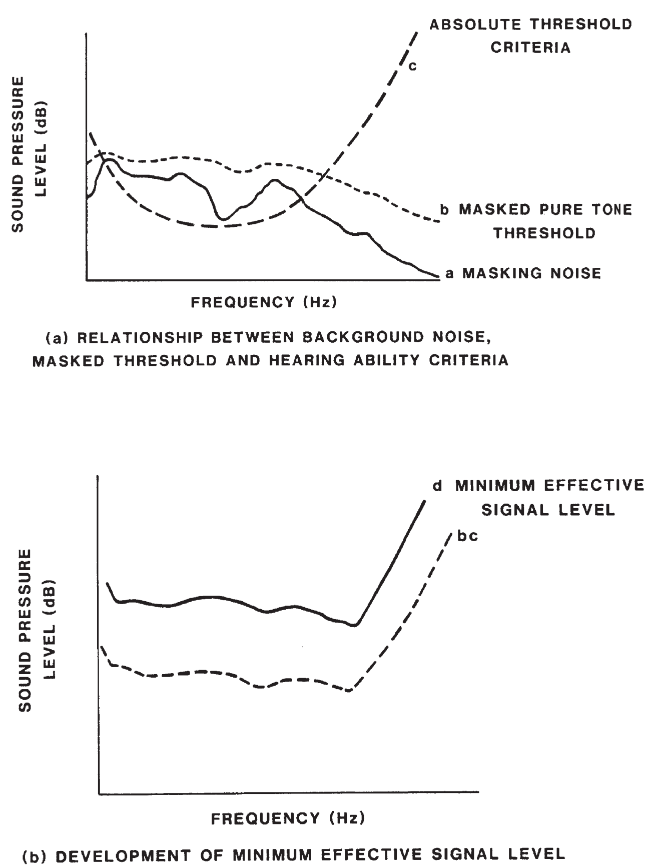

Figure 2. Signal audibility in noise.

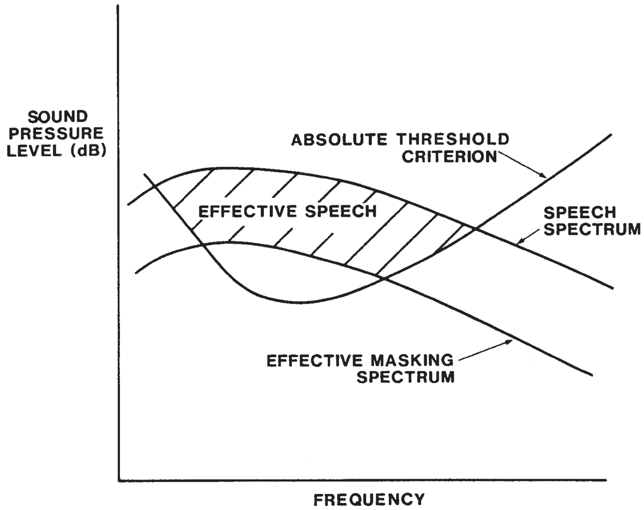

Figure 3. Components of speech audibility.

range in which speech will be effective. One of the more recent developments of this concept is the Speech Intelligibility Index, now adopted by the American National Standards Institute [37]. A Canadian group who looked at hearing standards for seagoing personnel describes the use of such an index in an operational setting [38]. They concluded that to reach a satisfactory SII cut-off value of 0.5 ('normally acceptable intelligibility'), hearing levels at the means of 0.5, 1, 2 and 3 kHz should not exceed a 'low fence' of 25 dB. This level corresponds to the 25 dB HL recognized by the American Association of Otolaryngology as the level at which disability starts to occur [39]. This should not be regarded as a cut-off value indicating where a person is safe or not safe, but as an action level where further thought, including task-based evaluation of ability, may be required.

Conclusion

Noise exposure and noise-induced hearing loss are still prevalent in the mining industry. Most of the risk comes from the need to use heavy machinery underground, but careful design and new technology and materials can be used to minimize this. Some degree of residual hearing protection may well be required, but this should be part of a well designed hearing protection programme. As hearing protection is so widely used, audiometric monitoring is essential and although otoacoustic emission techniques show promise for the future, pure tone audiometry is still the method of choice. A low fence of 25 dB HL at the means of 0.5, 1 and 2 kHz indicates that care will be needed with underground deployment.

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