Proposed Damage (Deafness) Risk Criteria for Exposure to Steady-State Broadband Noise: An Empirical Study

Chagok N.M.D, Gyang B.N.

Abstract— A-weighted equivalent continuous noise levels of nine companies/industries in Jos-Bukuru metropolis were determined by using Brüel & Kjaer Impulse Precision Sound Level Meter Type 2209 in conjunction with $\frac{1}{3}$-Octave Filter set Type 1616 and an audiometric test of five hundred and twenty four workers out of a total of seven hundred and ninety one volunteers interviewed were carried out. The physical measurements showed that in most of the workplaces e noise was predominantly broad-band, continuous and steady-state and the equivalent continuous noise levels in most of the workplaces were above the 85dBA TWA. The audiometric test results showed that noise-induced hearing loss were prevalent within the exposed workers. Regression analysis showed that the hearing loss which exhibited a variation with the octave-band frequency was directly depended on the exposure level, thereby supporting the equal energy hypothesis (EEH). The damage risk criteria for octave band frequencies between 250Hz and 8000Hz for male and female were computed from the empirically derived expression, as the sound pressure levels at and/or below which there would be no noise-induced hearing loss. An expression for age (presbycusic/sociocusic) hearing loss was also empirically derived which makes it possible to calculate the median threshold shift at various audiometric frequencies for a population exposed to a specified noise level for a specified time, including allowance for presbycusic/sociocusic loss.

Index Terms— Deafness, Broadband Noise, Threshold shift, Hearing loss, Damage Risk Criteria, Time Weighted Average, Octave Band Frequencies.

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1 INTRODUCTION

It is an incontestable fact that certain long-duration high-noise-level exposures will generate permanent hearing threshold shifts in man (Coles et al., 1968). Mechanization has increased, spread and intensified, and noise sources have become so much stronger that nowadays workers in different types of occupations are exposed to noise that may cause hearing loss (Passchier-Vermeer, 1974; Alberti, 1998; Berger et al., 1978; Cunniff, 1977; Ebeniro and Abumere, 1999). However, the transition (threshold) region below which these exposures become innocuous is a matter about which there is much debate. An important part of any noise control program is the establishment of appropriate criteria for the determination of an acceptable solution to the noise problem. Thus, where the total elimination of noise is impossible, appropriate criteria provide a guide for determining how much noise would be acceptable. At the same time, criteria provide the means for estimating how much reduction will be required. The required reduction in turn provides the means for determining the feasibility of alternative proposals for control, and finally the means for estimating the cost of meeting the relevant criteria (Smith et al., 1996). The basis for the determination of the Damage Risk Criteria (DRC) is the hearing damage.

During the 1950s and 1960s, there was considerable effort both in the U.K. and the U.S.A. to formulate damage risk criteria for hearing loss due to noise exposure. A certain degree of hearing damage was specified in terms of a so-called acceptable or tolerable hearing loss, quantified in terms of the proportions e.g. 50%, 10% or 1% of the exposed population suffering permanent threshold shift. The noise criteria were given typically as octave-band sound pressure levels expected to produce the specified hearing deficit in the stated proportion of those exposed.

These damage risk criteria were quite limited in their application to real situations. First, noises were assumed to be of constant character and at a constant level for long periods during the working day. Secondly, the damage risk criteria had a serious limitation of being applicable only to persons who worked in the same unchanging noise environment each day for decades, or indeed an entire working lifetime. Changing noise levels associated with changing work practice would invalidate the presumed damage risk. There was no way to account for potentially harmful noise exposure acquired over a series of different noise epochs, as might occur if a worker changed jobs over his or her working lifetime.

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Within the last forty (40) years it has been variously argued by different authors that the allowed maximum A-weighted sound levels necessary to protect industrial populations from incurring noise-induced permanent threshold shift (NIPTS) are 85dB (Kryter, 1973) to protect 90% of the population from exceeding a 16dB hearing threshold level averaged over 500, 1000 and 2000 Hz, 73dB (U.S. EPA, 1974) to protect virtually 100% of the population from exceeding a 5dB NIPTS at 4000Hz, or 80dB (Ward, 1975) to protect the median worker from incurring any NIPTS.

In recent years most industrialized nations that have recognised noise as an environmental pollutant and a serious threat to the quality of life of the people have established agencies and assigned to them responsibilities of regulating noise levels in different sectors of the environment. For example in the USA, the Environmental Protection Agency (EPA) occupational exposure regulation states that industry employers must limit the noise exposure of their employees to below 90dBA for an 8-hr period. This permitted maximum noise exposure is similar to the Greek standard, which considered an L_{eq} of less than 80dB as harmless, and suggested 85/90 dBA as a guide. No definite limit was specified, but both limits (85dBA or 90dBA) were accepted as long as certain conditions were met (Polyvios, 2002). People who work in most manufacturing industries are very much exposed to high level noise. Some of these people are exposed to an average of 85dB or more. Often there is a lack of concern for these workers because not all cases of hearing impairment are apparent. Many companies that needed hearing protection programs do not have them (Nash, 2000).

The equivalent continuous noise level of a time-varying noise L_{eq} is given by Cunniff (1977) as

$$L_{eq} = 10log_{10}(t_1x10^{L_1/10} + t_2x10^{L_2/10} + \ldots\ldots + t_nx10^{L_n/10})/T \quad (1)$$

where t_i is the time in hours the workers work in a section whose sound level reading is L_i. T is the total time,

Noise–induced hearing loss has been expressed in terms of a composite measure, the Sound Exposure Level (L_E) which is proportional to the total A-weighted sound energy received by the ear over the exposure time (Chagok, 2010; Chagok and Gyang, 2012). This concept (Equal Energy Hypothesis EEH) combines in a single parameter the sound pressure level and the duration of exposure to the noise. A simple statement of the EEH is that the trauma associated with a particular noise exposure is a monotonic function of the total amount of acoustic energy received by the ear.

The sound exposure level is the expression in decibels of the ratio of the weighted sound exposure to the reference sound exposure.

The A-weighted sound exposure level L_{AE} is therefore

$$\begin{aligned} L_{AE} &= 10\log\left(\int_0^T P^2(t)dt/P_0^2\right) \\ &= L_A + 10logT \end{aligned} \quad (2)$$

2 MATERIALS AND METHODS

Data were collected which permitted the establishment of a relationship between occupational noise exposure to the resulting noise induced hearing loss. Physical measurement of sound levels was done on the shop floors of companies and at the sites of industries within Bukuru and Jos metropolis which were identified to use machinery that generate high levels lof noise and had also granted permission for the research to be carried out in their premises as reported in Chagok and Gyang (2012). Overall A-weighted Sound Pressure Level and Sound Spectrum Levels were measured, at machine-operator positions in the companies/industries included in the research, using a *Brüel & Kjaer* Impulse Precision Sound Level Meter Type 2209 in conjunction with $\frac{1}{3}$-Octave Filter set Type 1616. The Pistonphone Type 4220 which generates 124dB$\pm$0.2dB at a frequency of 250Hz was used to calibrate the sound level meter. Measurements were taken during the usual business hours of 8:00 am and 5:00 pm, when the companies/industries were in production. Care was taken so that the measurements were made with the minimum interference with normal working patterns as possible and none of the measurements was influenced by external noise, such as aircraft or road traffic noise. These measurements were repeated on subsequent visits to confirm the values obtained.

The audiometric tests were conducted by a trained audiometric technician, supervised by a consultant within the ENT Unit of Evangel Hospital, Jos. Since people's susceptibility to NIHL varies widely, a large number of subjects were used to minimize the range of variability. Five hundred and twenty four (524) workers were tested out of a total of seven hundred and ninety one (791) workers interviewed.

Using the responses to a questionnaire administered to all workers in the factories and industries investigated, people with pre-existing conditions were excluded from the audiometric testing. Those excluded were people who: (i) were known to have hearing diseases (ii) have had military service in the artillery (iii) had participated in hunting or gaming sport using firearms (iv) had ever suffered head injuries/accidents and (v) had ear wax, boils, or hearing aids. As a precaution to minimise the effect of Temporary Threshold Shift (TTS), the subjects for the hearing tests were required to have been off-duty and away from industrial noise exposure for at least14 hours prior to testing.

The test equipment was a Beltone 112 Audiometer. The background noise levels during all tests satisfied the octave band level requirements of ANSI S3.1-1977. Otoscopic examination for wax and ear pathology was carried out prior to audiometric measurement. If wax was present, the ear was syringed and the assessment delayed for a minimum of 48 hours.

In the pure-tone audiometric test performed, sound beeps at test frequencies of 0.25, 0.50, 1.00, 2.00, 4.00 and 8.00 kHz were presented, commencing with the right ear, then the left ear. At each frequency the beeps were presented at randomly varying Sound Pressure Levels (SPL) and the volunteer (on prior instruction) was to indicate whenever he/she hears the sound.

The softest sound level a person heard at each pitch, for at least 50% of the time the sound was presented, was considered his hearing threshold. These thresholds were obtained for each test frequency and marked across the audiogram. Tests done with the padded headphones gave the air conduction thresholds and these were marked with a red O on the audiogram for the right ear, and with a blue X was for the left ear. If air conduction testing showed a severe hearing loss, bone-conduction vibrator was used to test for thresholds. The marks on the audiogram in this case were a < symbol for the right ear and a > symbol for the left ear. By this process the tests distinguished between sensor neural hearing loss and a conductive hearing loss.

3 Results and Analysis

3.1 Sound Pressure Levels in Work Environments

The noise data from the work environments was measured and tabulated. It was observed that the noise levels in given sections of the mills were very constant and continuous, and essentially devoid of any impulse components. In a given mill workmen were not restricted to only one workstation but moved from one workstation to another of varying noise levels. The time that a workman spent at each location was then estimated from data supplied (during interviews) by the foremen and supervisors of the mills. Thus the variations in sound level caused by a workman's movement among workstations were treated in the same manner as time-varying noise levels to compute the noise exposure for the workman. The noise level was also measured where the workers spent their one-hour break-time in the 9 hour shift and this was included in the calculations.

TABLE 1
Equivalent Continuous Noise Levels of the Mills

MILL	L_A	L_{AE}
A_1	92	137
A_2	87	132
A_3	90	135
B_1	85	130
B_2	89	134
C_1	89	134
C_2	86	131
D_1	75	120
D_2	67	112
E_1	102	147
E_2	106	151
E_3	104	149
F_1	100	145
F_2	98	143
F_3	97	142
G_1	94	139
G_2	88	133

Table 1 shows the Equivalent Continuous Noise Levels (LA) of the mills obtained using equation 1, and A-weighted Noise Exposure (LAE) obtained by using equation 2.

4 Noise-Induced Hearing Loss And Presbycusic/Sociocusic Loss

Audiometric evaluation of five hundred and twenty four (524) workers out of a total of seven hundred and ninety one (791) workers interviewed was performed.
Table 2 shows a typical variation of NIHL ($L_{50\%}$) with durations of exposure at octave band frequencies for workers in one of the mills and Table 3 shows variations of the sound pressure levels, exposure times, sound exposure levels and $L_{50\%}$ at the test frequencies.
Table 4 shows the values of the coefficients a and b as evaluated by the use of normal regression equations:

$$\sum L_{50\%} = Na + b\sum L_E$$
$$\sum L_E L_{50\%} = a\sum L_E + b\sum L_E^2 \quad (3)$$

for the regression equation of $L_{50\%}$ on L_E

$$L_{50\%} = a + bL_E \quad (4)$$

From the regression equation of $L_{50\%}$ on L_E i.e. $L_{50\%} = a + bL_E$ with a and b given in Table 4 it is possible to assess at each test frequency, the risk of noise-induced hearing loss $L_{50\%}$ caused by exposure to a certain level of broad-band noise for a known duration. Generally the hearing level of an individual of known age and exposure to a certain level of broadband noise, for a known period of time, can be estimated at each test frequency using Equation 4 with a and b given in Table 4 together with presbycusic/sociocusic loss calculated using regression equation

$$J = c + dy \quad (5)$$

J is the presbycusic/sociocusic loss, c and d given in Table 5 and y the age in years. The hearing level of a person who has worked in a noisy environment can be estimated using the expression

$$H = L_{50\%} + J = a + bL_E + c + dy \quad (6)$$

From the audiometric test results and the regression analysis the investigation yielded the following results:
A quantitative relationship between noise-induced hearing loss and noise exposure level. $L_{50\%} = a + bL_E$
Noise induced hearing loss $L_{50\%}$ for a given exposure level varies with frequency and sex. For a given exposure, $L_{50\%}$ for males was higher than $L_{50\%}$ for females at all frequencies.
The sound exposure level was recognized as the most appropriate quantity for assessing noise-induced hearing loss as it incorporates into one expression the effect of the sound pressure level and time of exposure.

TABLE 2
TYPICAL NOISE-INDUCED HEARING LOSS, $L_{50\%}$

Exposure Time in Yrs		0.25		0.50		1.00		2.00		4.00		8.00	
M	F	M	F	M	F	M	F	M	F	M	F	M	F
3.67	4.25	6.25	4.25	6.00	4.00	5.00	4.00	4.00	4.00	6.75	5.00	4.50	4.50
6.95	6.70	6.75	4.00	6.75	4.00	6.25	4.00	5.25	4.25	8.00	6.00	5.50	4.50
10.06	9.84	7.50	5.00	7.50	5.25	7.25	5.25	5.75	5.25	9.50	6.75	6.75	4.50
12.60	13.10	7.75	5.00	8.00	5.50	8.00	6.00	6.00	6.00	10.00	7.00	7.50	5.25
15.75	15.04	8.00	5.25	8.00	5.25	8.00	6.00	6.50	6.00	10.75	8.00	7.50	5.50
19.06	18.75	8.25	5.75	8.75	6.00	9.00	6.75	7.00	6.75	13.00	8.00	8.50	6.00
3.45	3.92	7.00	4.75	7.00	5.00	6.25	5.00	4.00	4.00	8.00	5.00	6.00	5.00
7.25	6.98	8.25	5.00	8.50	5.25	9.25	5.75	6.00	5.75	11.25	7.25	8.00	5.00
10.10	10.75	8.50	6.00	9.00	6.00	9.50	6.00	12.25	7.25	12.00	7.75	9.00	6.00
12.53	12.04	9.00	6.75	9.00	6.25	9.00	6.50	14.25	8.00	12.00	9.00	9.75	6.00
15.95	16.08	9.00	7.00	9.75	6.75	10.75	6.75	14.00	9.75	13.25	10.50	9.75	6.50
18.60	18.52	9.50	7.00	10.00	7.00	11.25	7.50	14.00	9.50	14.00	10.50	10.75	6.75
21.48	22.36	9.75	7.25	10.25	7.50	11.50	8.00	15.00	9.75	14.00	10.75	11.00	7.25

TABLE 4
VALUES OF THE COEFFICIENTS a AND b

Frequency Hz	a		b	
	M	F	M	F
250	-21.24	-17.82	0.30	0.24
500	-29.55	-20.18	0.39	0.26
1000	-44.96	-30.47	0.55	0.37
2000	-21.89	-37.08	0.36	0.45
4000	-51.43	-36.23	0.64	0.45
8000	-50.21	-20.26	0.60	0.27

TABLE 3
TYPICAL SOUND PRESSURE LEVEL, EXPOSURE TIME, SOUND EXPOSURE LEVEL AND $L_{50\%}$ AT TEST FREQUENCIES

SPL (dBA)	Exposure Time (Yrs)		Exposure Level L		0.25		0.5		1		2		4		8	
	M	F	M	F	M	F	M	F	M	F	M	F	M	F	M	F
85	3.67	4.25	91.00	91.00	6.25	4.25	6.00	4.00	5.00	4.00	4.00	4.00	6.75	5.00	4.50	4.50
	6.95	6.70	93.00	93.00	6.75	4.00	6.75	4.00	6.25	4.00	5.25	4.25	8.00	6.00	5.50	4.50
	10.06	9.84	95.00	95.00	7.50	5.00	7.50	5.25	7.25	5.25	5.75	5.25	9.50	6.75	6.75	4.50
	12.60	13.10	96.00	96.00	7.75	5.00	8.00	5.50	8.00	6.00	6.00	6.00	10.00	7.00	7.50	5.25
	15.75	15.04	97.00	97.00	8.00	5.25	8.00	5.25	8.00	6.00	6.50	6.00	10.75	8.00	7.50	5.50
	19.06	18.75	98.00	98.00	8.25	5.75	8.75	6.00	9.00	6.75	7.00	6.75	13.00	8.00	8.50	6.00
89	3.45	3.92	94.00	94.00	7.00	4.75	7.00	5.00	6.25	5.00	4.00	4.00	8.00	5.00	6.00	5.00
	7.25	6.98	98.00	98.00	8.25	5.00	8.50	5.25	9.25	5.75	6.00	5.75	11.25	7.25	8.00	5.00
	10.10	10.75	99.00	99.00	8.50	6.00	9.00	6.00	9.50	6.00	12.25	7.25	12.00	7.75	9.00	6.00
	12.53	12.04	100.00	100.00	9.00	6.75	9.00	6.25	9.00	6.50	14.25	8.00	12.00	9.00	9.75	6.00
	15.95	16.08	101.00	101.00	9.00	7.00	9.75	6.75	10.75	6.75	14.00	9.75	13.25	10.50	9.75	6.50
	18.60	18.52	102.00	102.00	9.50	7.00	10.00	7.00	11.25	7.50	14.00	9.50	14.00	10.50	10.75	6.75
	21.48	22.36	102.00	102.00	9.75	7.25	10.25	7.50	11.50	8.00	15.00	9.75	14.00	10.75	11.00	7.25

We now seek to establish the damage risk criteria at the octave band frequencies between 250Hz and 8000Hz to preserve hearing at the frequencies important for good speech recognition. This damage risk criterion (called New Damage Risk Criterion NDRC) would be based on the empirically derived expression (equation) using data collected from exposure to noise.
For zero (0) noise-induced hearing loss at any octave band frequency (for 10 years of exposure) we have from equation (4)

$$0 = a + b(L_A + 10\log 10)$$

$$L_E = L_A + 10\log T$$

This gives

$$L_A - \frac{a \quad 10b}{b} \qquad (7)$$

The values for the damage risk criteria are as shown in table 6.

TABLE 5
VALUES OF THE COEFFICIENTS c AND d FOR PRESBYCUSIC/SOCIOCUSIC LOSS

Freq	Age	c		d	
		M	F	M	F
250	20-45	-1.32	-0.95	0.097	0.08
	50-75	-16.48	-11.14	0.39	0.27
500	20-45	-1.30	-0.95	0.097	0.08
	50-75	-20.14	-7.95	0.47	0.23
1000	20-45	-1.32	-1.32	0.10	0.10
	50-75	-21.38	-13.38	0.49	0.33
2000	20-45	-3.61	-2.09	0.18	0.13
	50-75	-36.38	-22.10	0.85	0.54
4000	20-45	-5.50	-4.17	0.35	0.25
	50-75	41.10	-31.14	1.14	0.87
8000	20-45	-10.10	-9.54	0.53	0.46
	50-75	-66.86	-56.71	1.69	1.41
3000	20-45	-4.93	-4.16	0.28	0.23
	50-75	-38.00	-34.00	1.00	0.84
6000	20-45	-9.75	-9.52	0.53	0.46
	50-75	-47.14	-33.76	1.31	0.98

TABLE 6
VALUES OF THE L_A AT THE OCTAVE BAND FREQUENCIES

Frequency Hz	L_A (dBA)	
	M	F
250	61	64
500	66	68
1000	72	72
2000	51	72
4000	70	71
8000	74	65

These are the sound pressure levels at and/or below which, there would be no noise-induced hearing loss in male and female for ten (10) years of exposure. This New Damage Risk Criteria (NDRC) for noise hazard follows from the empirically derived expression. It would be observed that the NDRC for females is higher than for males except for 8000Hz where that for males is higher and at 1000Hz where they are equal. For simplicity, L_A at 4000Hz (resonant frequency of the ear) (i.e. 70dBA and 71dBA) could be used as noised-induced hearing loss begins to show at that frequency and spreads to other frequencies.

5 CONCLUSION AND RECOMMENDATIONS

Physical measurements of sound noise pressure levels showed that most factory workers are exposed to hazardous levels of noise. The audiometric test results obtained from this investigation confirmed this by showing measurable NIHL over and above any age effect. A quantitative relationship between noise-induced hearing loss and noise exposure was empirically derived. The damage risk criteria for noise-induced hearing loss at octave band frequencies between 250Hz and 8000Hz were computed. Thus, the median threshold shift at various audiometric frequencies for a population exposed to a specified noise level for a specified time can be assessed, including allowance for presbycusic loss. Perplexing differences in susceptibility to NIHL leading to differences in damage risk criteria were observed between males and females for whom the researchers were not able to find any explanation in the literature. While this view was not investigated, a suggested contributing factor is that, culturally, females almost always wear a turban-like head dress – which often covers their ears. The head dress might be acting as ear-muffs. Even when the head-cloth does not actually cover the ears, its sound absorption may reduce the sound level around the ears. From this work, the following recommendation is made: workers exposed to high levels of noise should wear ear protection. The differences in susceptibility accounting for the differences in the damage risk criteria between male and female could be a subject for further investigation.

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