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A PROCEDURE FOR QUANTIFYING THE BENEFIT AND COST EFFECTIVENESS OF NOISE CONTROL MEASURES

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INTRODUCTION

The personal daily noise exposure is the accepted means of assessing an individual's risk of incurring noise induced hearing damage [1]. However, in situations where a number of workers is exposed to noise from a number of noise sources, as found in many factories, the personal daily noise exposure does not identify the most significant noise sources. Nor in fact can it provide an overall picture of the effectiveness of a noise control measure. Of course the benefit to an individual is correctly assessed by comparing their 'before and after' personal exposures, but, when several workers are affected by the change to varying extents, a straightforward before and after comparison of overall effectiveness is no longer possible.

Such situations can be, and frequently are, extremely complicated: all the workers may be exposed to noise from all the sources but in differing proportions, machines operate for different periods and at different levels, workers move and so are affected by different noise sources at different times. It is seldom obvious which are the most significant noise sources overall and even less so which combinations of noise control measures should be implemented for optimum effect. The lack of a proper procedure for quantifying the overall benefit in such complex situations has led to many mistakes in the past resulting in ineffective noise control programmes, sometimes at great cost. This situation could be improved by providing a single figure rating to quantify the overall benefit to the workforce. Such a procedure should allow all the above complications to be dealt with, and should be based on the accepted principle of noise exposure.

In this paper a procedure is described in which the concept of personal daily noise exposure is extended so as to provide firstly, a system for rank ordering noise sources in terms of their overall contribution to noise exposure, and secondly a single figure rating such that the benefits of different noise control options and combinations of options can be properly compared. It will be seen that this can be extended simply to give a single figure rating for the relative cost effectiveness of the various options.

'SOURCE NOISE EXPOSURE' AND 'WORKFORCE NOISE EXPOSURE'

The personal daily noise exposure level of a worker ($L_{ep,d}$) is the equivalent continuous sound level normalised to an 8 hour working day, normally expressed in dBA [1], [2], [3]. This can equally well be expressed in terms of the total fractional exposure [3], or as units of

Pa^{2}hours, both of which simply express the personal exposure in linear rather than logarithmic units. In this context the latter two definitions are far more convenient, and fractional exposure will be used exclusively from now on. For convenience the total fractional exposure accumulated by a worker in a day will be referred to as the 'personal exposure', defined as

$$F_{wn} = \text{antilog}\,[0.1(L_{ep,d}-90)] \qquad 1$$

In equation 1 the subscript "wn' indicates that this is the personal exposure of worker n. In the definition given by equation 1, 100% exposure corresponds to and $L_{ep,d}$ of90dBA, but 85 dBA or an other figure could have equally been used. (Note that here, and in all the following definitions involving noise exposure, the assessment period would normally be a working day, but the term 'daily' has been dropped for brevity.)

In most cases, particularly in factories the noise level at any time is made up of contributions from many noise sources. The concept of fractional exposure can be extended to express the exposure of the worker as the sum of the exposures due to each individual noise source:

$$F_{w1} = f_{w1,s1} + f_{w1,s2} + \ldots + f_{w1,sn} \qquad 2$$

Here, fw1s1 represents the fractional exposure which would be caused to worker w1 by source s1 if only that source were operational, all other sources being silent. Similarly, fw1s2 is the contribution to worker w1's exposure from source s2 etc. These fractional exposures contributions are not normally quantified as part of the noise exposure assessment but could be measured by running noise sources individually and in practice are frequently found by estimation. The fractional exposure contributions take into account both the noise level and the exposure time following exactly the normal rules, the only difference is that here we are dealing with a contribution from a particular source at the ear rather than the total level.

In most cases workers in different parts of the factory will be exposed to noise from the same sources but in differing proportions. The exposure of worker w2 due to sources s1, s2 etc. is given by:

$$F_{w2} = f_{w2,s1} + f_{w2,s2} + \ldots + f_{w2,sn} \qquad 3$$

and this is easily extended to cover all those workers so exposed in a matrix.

	Source 1	Source 2		Source n	All sources
Worker 1	$f_{w1,s1}$	$f_{w1,s2}$	. . .	$f_{w1,sn}$	F_{w1}
Worker 2	$f_{w2,s1}$	$f_{w2,s2}$	. . .	$f_{w2,sn}$	F_{w2}
. . .	. . .	. . .	. . .	. . .	. .
Worker m	$f_{wm,s1}$	$f_{wm,s2}$	. . .	$f_{wm,sn}$	F_{wn}
All workers	F_{s1}	F_{s2}	. . .	F_{sn}	$F_{workforce}$

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Summing across the rows of the matrix, the totals on the right hand side are the personal exposures for each of the workers as obtained in standard noise exposure assessments. Summing down the columns, the figures in the bottom row represent the contribution to the exposure of the entire workforce due to the individual noise sources. These numbers will be termed 'source noise exposures'. One can see immediately that the largest source noise exposure identifies the noise source causing the greatest overall exposure. It will also be seen that rank ordering of the sources in terms of importance is possible using this row.

The figure on the bottom right of the matrix (equation 4) can be obtained either by summing the personal exposures in the right hand column, or the source exposures along the bottom row. This is the most important parameter in this discussion and represents the cumulative noise exposure of all the workers. It will hence be termed the 'workforce noise exposure'. The significance of this parameter is that it will provide a relative measure of the overall benefit of different noise control options as a single figure rating no matter how complex the situation.

The procedure for estimating the overall benefit is as follows: the estimated reduction in exposure due to the proposed change on a noise source (whether this be a reduction in noise level, exposure time, or both) is simply applied to the appropriate column. The workforce noise exposure is then recalculated to provide a single figure comparison before and after noise control. The number of units by which the workforce noise exposure is reduced then provides a direct measure of the benefit to the workforce.

The only non standard step in the above derivation is the summing of the exposures of the various workers down the columns. This step can be justified on the grounds that the established basis for exposure assessment is that <u>dose</u> is the important parameter, irrespective of how this is accumulated throughout the day. So, a given personal exposure could be due to relatively long periods of exposure at relatively low levels or shorter periods at higher levels etc. In the same way, the workforce exposure could be made up by relatively low exposures affecting a large number of workers or that of a small number of workers subject to high exposures etc. It represents the total noise dose of the workforce and is therefore the most relevant single figure representation of their combined exposure.

However, as with any single figure rating some information is lost, and one should be careful to distinguish between overall noise exposure and overall risk of incurring hearing damage. For example, it is possible to think of situations where to reduce the workforce noise exposure to the lowest level requires reduction of a large number of small exposures in favour of reduction of a few high level exposures. It is not immediately obvious whether this corresponds with the greatest overall reduction in risk. Furthermore, this may not comply with local legislation if it leaves workers exposed above some action level. Clearly then, some care is needed in using this approach. Nevertheless, with appropriate care the procedures described should provide a useful conceptual aid and practical tool. An interesting extension would be to weight the personal noise exposures according to the risk of incurring damage at that level of exposure; the sum of these 'personal risk factors' would then correspond directly to the statistical risk of the entire workforce. However, further discussion of this possibility is outside the scope of this paper.

EVALUATION OF COST EFFECTIVENESS

Finally, the concept of workforce noise exposure can be used to provide an objective measure of the relative cost effectiveness of a particular noise control option. Quite simply, the cost of implementation is divided by the appropriate reduction in workforce noise exposure to give a 'cost per unit of workforce exposure removed'.

ILLUSTRATIVE CASE STUDY

An industrial workshop is shown in figure 1 for which three options are being considered for noise control.

The following workers are employed:

w1 one press operator who spends 8 hours per day at the press

w2-4 three workers in the finishing bay working independently, each operating hand held drills, grinders and air jets for a total of 1.5 hours per day

w5-9 five assembly workers performing quiet operations but subjected to noise from all sources for 8 hours per day

w10-11 two trolley operators who spend 1.5 hours per day loading at the press, 3 hours loading and unloading at the finishing bay, 1.5 hours unloading at the assembly line and the remaining 2 hours of their shift in a quiet storeroom

The major noise sources in the factory are:

s1 a dust extract system generating a continuous 86dBA constant throughout the factory

s2 the press, operating for 1 hours per day causing contributions of 101dBA at the operators position, and 90dBA at both the assembly line and finishing bay

s3 hand held drills, grinders and air jets used in the finishing bay with a total on-time of 1.5 hours per day per worker. The Leq of the finishing operations is 98dBA at the operators ear, and drops to 90dBA at the adjacent finishing workers' ear. The contribution of these operations to the press operator is 82dBA and to the assembly line workers 85dBA

Note that the above levels quoted are L_{eq}s for the operation as a whole. Furthermore the levels are contributions, that is, due to that process alone and excluding noise from other operations

The fractional exposure contributions to worker wn due to source sm are calculated according to:

$$f_{wn,sm} = \frac{t_{wn,sm}}{8} \text{antilog}\left(\frac{L_{wn,sm} - 90}{10}\right) \quad 5$$

where $L_{wn,sm}$ is the sound level contribution (L_{Aeq}) to worker n due to machine m, and $t_{wn,sm}$ is the time of exposure at that level.

For example the figure for a trolley operator due to the dust extract system is:

$$f_{w10,s1} = \frac{6}{8} \text{antilog}\left(\frac{86 - 90}{10}\right) = 0.299 \quad 6$$

The trolley operators' exposure contribution due to the finishing operations is calculated by summing the contributions whilst they are at the press (3 contributions of 82dBA for 1.5 hours), the assembly line (3 contributions of 85dBA for 1.5 hours) and the finishing line (3 contributions of 90dBA for 3 hours) ie

$$f_{w10,s1} = 3x0.1875x\left\{\frac{1.5}{8} \text{antilog}\left(\frac{82 - 90}{10}\right) + \frac{1.5}{8} \text{antilog}\left(\frac{85 - 90}{10}\right) + \frac{3}{8} \text{antilog}\left(\frac{90 - 90}{10}\right)\right\} = 0.261 \quad 7$$

(The factor 3x0.1875 appears because the operations of each of the three finishing workers take place for 18.75% of the time and the movement of the trolley operator is not correlated with their activity.)

Workers in the finishing bay receive a single contribution of 98dBA for 1.5 hours due to their own operations and two contributions of 90dBA, also for 1.5 hours due to their neighbours. It does not matter whether they create noise at the same time or separately, the cumulative dose is the same.

Other contributions to the worker's exposures are calculated in a similar way, and the complete exposure matrix is given in table 1. It can be seen that although the press is the noisiest machine its overall contribution to noise exposure is less than either of the other two sources.

The noise control options being considered are as follows.

(a) treatment of the press with a reduction in its contribution of 8dBA, cost £15000

(b) a change in production allowing finishers to complete their operations in 80% of the time, cost £4000

(c) treatment to the dust extract system giving a reduction in its contribution of 3dB, cost £1500

The workforce noise exposures are recalculated by reducing the figures in the appropriate column. For example for option c, all figures in column 1 are reduced by half. The recalculated workforce noise exposures are summarised in table 2. The option giving the largest overall reduction is the treatment of the press, but this is also the least cost effective option. From table 2 it would be preferable to carry out both options b and c, as this would provide greater overall benefit as well as being more cost effective than option a.

Table 2 Comparison of benefits for noise control options a-c

	Option a	Option b	Option c
Workforce exposure without mod.s	13.66	13.66	13.66
Workforce exposure with mod.s	10.88	12.42	11.57
Reduction in workforce exposure	2.78	1.24	2.09
Cost of mod.s	£15000	£4000	£1500
Cost per unit of reduction	£5396	£3226	£717

CONCLUSIONS

Personal daily noise exposure is the accepted method of assessing an individual's risk of suffering noise induced hearing damage. Two complementary concepts have been introduced here as aids to identifying appropriate noise control measures in complicated situations and evaluating their overall success when a number of workers benefit by differing amounts.

'Source noise exposure' quantifies the contribution of a noise source to the exposure of the whole workforce and hence allows rank ordering of noise sources in terms of their overall importance.

'Workforce noise exposure' provides a measure of the overall exposure of the workforce in a single figure rating. A simple before and after comparison then quantifies the overall benefit to the workforce of a noise control option or combination of options no matter how complicated the situation. An objective measure of the cost effectiveness of these options is then straightforward.

REFERENCES

[1] EEC, Council Directive of 12 May 1986 on the protection of workers from the risks related to exposure to noise at work. 86/188/EEC (1986) .

[2] HEALTH AND SAFETY EXECUTIVE, Statutory Instrument no1790. The Noise at Work Regulations 1989. (1989).

[3] HEALTH AND SAFETY EXECUTIVE, Noise at work: Noise assessment, information and control. Noise Guides 3 to 8, HMSO (1990)

Table 1 Exposure matrix

	Dust Extract	*Press*	*Finishing*	*Personal exposure*
W1	0.398	1.574	0.089	2.061
W2	0.398	0.125	1.558	2.081
W3	0.398	0.125	1.558	2.081
W4	0.398	0.125	1.558	2.081
W5	0.398	0.125	0.178	0.701
W6	0.398	0.125	0.178	0.701
W7	0.398	0.125	0.178	0.701
W8	0.398	0.125	0.178	0.701
W9	0.398	0.125	0.178	0.701
W10	0.299	0.365	0.261	0.925
W11	0.299	0.365	0.261	0.925
TOTAL	4.18	3.30	6.17	13.66

Fig 1. Example factory layout