COMMENT ON “EXCHANGE RATE” IMPOSED IN THE LOCAL FACTORIES AND INDUSTRIAL UNDERTAKINGS (NOISE AT WORK) REGULATION

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ABSTRACT

An exchange rate of 3 dB is imposed for noise control on safety issues in the local Factories and Industrial Undertakings (Noise at Work) Regulation (2000). Suitability of this value will be reviewed in this paper. The background of the exchange rate is discussed, together with other values of 5 dB and 6 dB used earlier in elsewhere. Attempts are made to study the scientific basis of these values by understanding the principles behind. The health effects of noise exposure corresponding to the requirements are pointed out. It is proposed that setting too tight a regulation might not be good. Changing the exchange rate of 3 dB to 5 dB, or even 6 dB, would imply significant different exposure time of labours to different aural environment. Field measurement for safety aspects of exposing local workers to noise should be carried out.

1. INTRODUCTION

Labours in Hong Kong are protected from exposure to noise in their working environment by the Factories and Industrial Undertakings (Noise at Work) Regulation (FIU code) [1,2] held responsible by the Labour Department. This was set up in 1992 to provide statutory controls to protect employees [1,2] to ensure, at least, the following:

- Assessments of noise exposure to be carried out;
- Ear protection zones to be demarcated;
- Distances for noisy machines or tools to be specified;
- Suitable approved ear protectors to employees to be provided by the proprietors;
- Ear protectors to be approved;
- Noise exposure to be reduced;
- Approved ear protectors and noise control equipment provided to be used fully and properly; and to be maintained properly; and
- Information to employees to be provided.

Guidance notes were issued by the Occupational Safety and Health Branch of the Labour Department in 1998 in an attempt to explain the Regulation in a simpler format [2]. This will facilitate proprietors to discharge their legal obligation and help to point out the rationale behind many numerical data specified and imposed [1,2]. Explanations have not yet been clearly spelled out in the regulation though there are numerous reports appeared in the literature [3-12].

Exchange rate is the increment (or decrement) of the sound levels (in dB) that requires the halving (or doubling) of the exposure time [3], or the rate at which exposure accumulates or the change in dB time-weighted average (TWA) for halving/doubling of the allowable exposure time [4]. It is the trade-off relationship between an increase (or decrease) in sound level and the corresponding change in the allowed exposure duration [4,5]. It can also be named as “doubling rate”, “trading ratio” or “time-intensity trade-off” [3,6]. Different values of exchange rates at 3 dB, 5 dB and 6 dB were used by various regulatory bodies [4,7,8]. Questions used to be raised on taking 3 dB as the exchange rate. Eventhough the rate of 3 dB is supported by the “equal energy rule” which is more scientific [3,6], other values such as 5 dB or even 6 dB might still be suitable [7,8]. The exchange rate of 5 dB is based on the actual physiological response of human with the temporary threshold shift being measured [5,9]. The value of 6 dB is based on the “equal pressure” rule [7].

It is obvious that a safe and healthy environment should be provided for the workers. However, rules should be set up with more scientific support, not just simply copying from overseas guides. Background of different values of exchange rates are discussed in this paper.

2. POTENTIAL HEALTH EFFECTS OF EXPOSURE TO NOISE

Exposure to noise would lead to hearing loss. Hearing threshold, taken as the sound pressure level (SPL) at different frequencies at which
sounds are just detected, is the main parameter for assessing hearing loss. Response on the threshold before and after exposure to loud noise will be measured [9]. This should be distinguished from the permanent hearing loss caused by natural aging known as “Presbycusis”. There, hearing loss starts from the higher frequencies to lower frequencies with the lost magnitude increases with age. The elderly might gradually become deaf permanently and the causes are not too well understood. Deterioration of the inner ear, nerves to the brain, and possibly areas of the brain (cortex) are observed [9].

Basically, health effects can be classified into three types:

- **Temporary Threshold Shift (TTS<sub>2</sub>)**

Hearing threshold 2 mins after exposure to a noise is usually taken as the temporary hearing loss [3,4,9-11]. The degree of threshold shift is a function of the frequency and duration of the noise. TTS<sub>2</sub> is found to be increased linearly with SPL. This relation holds at least for moderate levels of sound level from 80 to 105 dB with exposures less than 8 hrs.

- **Noise-Induced Permanent Threshold Shift (NIPTS)**

This can be understood [e.g. 9] as the permanent hearing loss by measuring the changes in hearing sensitivity, resulting from exposure to noise. There are only fairly clear understandings on how NIPTS would be varied with exposure to occupational noise [8,9]. Survey studies suggested basically a very little effect for exposure to noise below 80 dB(A) over a working day. Exposure to 85 dB(A) might lead to a hearing loss of the order of 15 dB at high frequencies, though some people will not be affected. Exposure to noise above 90 dB(A) for a working day will lead to a hearing loss well in excess of 20 dB for most people. This point should be considered while setting up the necessary action levels such as those in the local FIU code [1,2]. A pictorial view is clearly shown in Fig. 1.

- **Acoustic trauma**

This is the hearing damage having “immediate” and “permanent” effects. It is believed that upon exposure to high-level but short duration noise (impulse) of SPL exceeding 140 dB, the delicate inner ear tissues would be stretched beyond the elastic limits, ripped and torn apart [12]. Therefore, maximum SPL of the impulsive noise will be a key factor in damaging the ear mechanically. Single explosive events are obvious examples which include hitting the eardrums by welding sparks, blows to the heads, detonating firecrackers near the head with SPL of 170 dB, gun shots, high-powered rifles, or pistol shots of SPL from 160 to 170 dB [12].

![Fig. 1: NIPTS results [9] and action levels in the local FIU code [1,2]](image-url)
3. DAILY PERSONAL NOISE EXPOSURE $L_{Ep,d}$

As defined in the FIU code [1,2], $L_{Ep,d}$ (in dB(A)) is the daily personal noise exposure of workers to fluctuated noise levels throughout the working day, with 8 hrs of exposure to match with working hours (also known as the 8-hour average sound levels) [5].

$$L_{Ep,d} = 10 \log_{10} \left( \frac{1}{T_0} \int_0^{T_0} \left( \frac{P_A(t)}{P_0} \right)^2 dt \right)$$

(1)

where $T_0$ is the averaging time agreed by the regulations, say kept at 8 hrs or 28,800 s in the FIU code [1,2]; $P_0$ is the threshold of hearing of $2 \times 10^{-5}$ Pa; and $T_e$ (in s) is the duration of the personal exposure to noise of sound pressure $P_A(t)$ (in Pa) taken as the time-varying value of A-weighted instantaneous values. This is in fact the 8-hr $L_{Ep,d}$ as discussed in the literature [13]. There, 24-hr equivalent exposure by taking $T_0$ as 24 hrs was also discussed.

This can be expressed as a summation over the personal exposure time $T_1, T_2, \ldots, T_n$ (in hrs) at noise levels $L_{PA1}, L_{PA2}, \ldots, L_{PA_n}$ (in dB(A)) of the ith measurement with exposure time $T_i$ (in hrs) as:

$$L_{Ep,d} = 10 \log_{10} \left( \frac{T_1}{8} 10^{L_{PA1}/10} + \frac{T_2}{8} 10^{L_{PA2}/10} + \ldots + \frac{T_n}{8} 10^{L_{PA_n}/10} \right)$$

(2)

with

$$\sum_{i=1}^{n} T_i = T_e$$

$L_{Ep,d}$ can be expressed in terms of the noise level $L_{PA_i}$ as:

$$L_{Ep,d} = 10 \log_{10} \left( \frac{1}{8} \sum_{i=1}^{n} T_i \cdot 10^{L_{PA_i}/10} \right)$$

(3)

4. ACTION LEVELS IN THE FIU CODE

Three action levels of noise are specified in the FIU code [1,2] as below:

- First action level for $L_{Ep,d}$ of 85 dB(A);
- Second action level for $L_{Ep,d}$ of 90 dB(A); and
- Peak action level for noise reaching a peak sound pressure level of 140 dB or peak sound pressure of 200 Pa.

Actions to be taken for $L_{Ep,d}$ lying between the first and second action levels are:

- For employees being exposed to noise between the first and second action levels, suitable approved types of ear protectors should be provided on the employer’s request [2]. Such a requirement on the proprietors to provide suitable ear protectors to the employees might be exempted where the use of ear protectors might cause risk to the safety of the employees or of any other person.

- Certain basic steps should be taken when the employees are exposed to noise at or above the first action level [2].

An assessment of noise exposure is required when the employees are likely to be exposed to noise at or above the first or peak action level. The assessment includes identifying all the employees who are so exposed and need ear protection. Sufficient information should be provided such as informing the employees that there is a noise hazard and appropriate actions should be taken in order to minimize the risk of hearing damages. When a noisy machine which normally emits noise exceeding the first action level is installed, a noise assessment is always required [2].

Actions to be taken for $L_{Ep,d}$ lying between second and peak action levels are:

- Suitable ear protectors should be provided to all employees when they are exposed to noise at or above the second action level (i.e. $L_{Ep,d}$ 90 dB(A)) or at or above the peak action level (i.e. 140 dB) [2].

Any areas with the employees being exposed to the second level or above or to the peak action level or above in any part of an industrial undertakings should be marked clearly by the proprietors as the “ear protection zones”. Approved ear plugs and ear muffs should be worn whenever the employees are exposed to noise at or above the second or peak action level, and also when they enter the “ear protection zones” [2].

Additional actions have to be taken when the employees are exposed to noise at or above the second or peak action level [2].
When the employees are exposed to infrequent but loud impact noise such as from heavy hammering on metal or explosive noise such as from the cartridge-operating fixed tools, the peak action level might be exceeded eventhough the second action level is not exceeded. Then, assessments of the peak sound pressure are required [2].

When the employees are exposed to noise at or above the first or peak action levels, the noise exposure to the employees should be reduced, so far as is practicable, other than by the approved ear protectors, by the proprietors. This can be achieved by implementing a programme of control measures. A long-term programme, including regular reviews of the feasibility of further noise reduction and considering the development of the noise control techniques should be carried out [2].

As explained above, how NIPTS would be varied with exposure to occupational noise is not too clear [8,9]. But field studies concluded that exposure to noise below 80 dB(A) over the working day has little health effect. Exposure to 85 dB(A) might produce a hearing loss of the order of 15 dB at high frequencies for some people. Noise at 90 dB(A) over the working day is very likely to produce a hearing loss above 20 dB.

A possible reason for setting up the first and second action levels to be at 85 dB(A) and 90 dB(A) respectively in the regulation is perhaps related to NIPTS as shown in Fig. 1. As reported in literature, NIPTS was firstly found in the region of 4000 Hz, the frequency which the ear is most sensitive to sound [9]. NIPTS then increases with increasing exposure to noise and efforts due to other frequencies shown. Twenty years of chronic exposure to noise make the onset and severity of the permanent threshold shifts become faster.

5. THE EQUAL ENERGY RULE

In most countries, the trading relation between time and level is based on the “equal energy rule” [3,6,7]. It is used to specify the maximum exposure times for louder noises. Exposing to two different noises of sound pressures $P_1$ and $P_2$ (in Pa), i.e. sound levels $L_{eq1}$ and $L_{eq2}$ (in dB(A)) with exposure time $t_1$ and $t_2$ (in s), the “equal energy rule” gives:

$$\int_0^{t_1} \left( \frac{P_1}{P_0} \right)^2 dt = \int_0^{t_2} \left( \frac{P_2}{P_0} \right)^2 dt$$

(4)

Defining $L_{eq1}$ and $L_{eq2}$ as in equation (1), putting in equation (4) gives:

$$\frac{t_2}{t_1} = 10^{\frac{(L_{eq1} - L_{eq2})}{10}}$$

(5)

Taking $P_1$ and $P_2$ as constant values in equation (4) gives:

$$t_1 P_1^2 = t_2 P_2^2$$

(6)

Therefore,

$$L_{eq1} - L_{eq2} = 3 \text{ dB}$$

(7)

or doubling the exposure time ($t_2 = 2t_1$) would reduce the noise exposure level by:

$$L_{eq1} - L_{eq2} = 3 \text{ dB}$$

Mathematical derivation of the above equations is shown in Appendix A. In view of equation (6), exposure time $t_2$ can be extended to 4$t_1$ if $P_2$ is reduced to 0.5 $P_1$. Further, the following can be observed from equation (7):

- If $L_{eq1}$ is greater than $L_{eq2}$ by 3 dB, then $t_2 = 2t_1$.
- If $L_{eq1}$ is less than $L_{eq2}$ by 3 dB, then $t_2 = 0.5t_1$.

If 90 dB(A) for 8 hrs is the acceptable limit, for every halving of exposure time, the overall level can be increased by 3 dB. With a halving rate of 3 dB, a noise dose of 90 dB(A) for 8 hrs would be equivalent to 93 dB(A) for 4 hrs or 96 dB(A) for 2 hrs.

6. OTHER EXCHANGE RATE VALUES

The exchange rate of 5 dB was proposed based on TTS2, though there was no very clear description in the literature [4,5,9]. In fact, the exchange rate of 5 dB is not used in many new versions of standards. It is believed [e.g. 9] that decreasing the SPL (in dB) by 5 dB to (SPL - 5) dB can double the exposure time from $T_0$ (in min) to 2$T_0$ (in min), to get the same TTS2. A pictorial presentation is shown in Fig. 2.

An exchange rate of 6 dB can be derived from the “equal pressure” rule [e.g. 8],
\[ \int_0^{t_1} \left( \frac{P_1}{P_0} \right) dt = \int_0^{t_2} \left( \frac{P_2}{P_0} \right) dt \]  
(8)

Taking \( P_1 \) and \( P_2 \) to be of constant values over the exposure period gives:

\[ t_1 P_1 = t_2 P_2 \]  
(9)

For \( P_2 \) taking half of \( P_1 \), \( t_2 \) will be double that value for \( t_1 \). Again, similar analysis for the above as in Appendix B gives:

\[ L_{\text{Eq}(1)} - L_{\text{Eq}(2)} = 6 \text{ dB} \]  
(10)

7. SAFE EXPOSURE LEVEL

There were extensive studies in the literature on determining the cutoff noise levels below which operators can be exposed to for an 8-hr day without increased risk of hearing loss [14]. With correct interpretation of the measurements made in the workplaces and appropriate actions taken, the concept of a maximum daily noise “dose” is essential. A (Maximum) permissible exposure limit (PEL) and an action limit (AL) to prevent noise hazards were proposed by the Occupational Safety and Health Administration (OSHA), US Department of Labor, USA [15]. PEL is defined to be the TWA, which when exceeded, requires feasible engineering and administrative controls, and mandatory hearing protection [4]. In addition, the threshold limit values (TLVs) for noise (sound) pressure levels have been used by the American Conference of Governmental Industrial Hygienists (ACGIH) to represent conditions to which workers may be repeatedly exposed without adverse effect on their ability to hear and understand normal speech [16].

These works lead to two noise exposure standards commonly used:

- OSHA’s Standards [4,5,15]

PEL (8-hour equivalent) is specified to be 90 dB(A) and AL is taken as 85 dB(A) TWA for an 8-hr exposure in USA [4,5,15]. At AL of 85 dB(A), a hearing conservation program which includes record keeping, noise surveys, and audiometric testing of employees is required to be implemented. Note that AL is a threshold trigger to remind the potential hazard of noise exposure, and is widely accepted that exposure time should be shorter for exposing a worker to noise levels higher than the PEL.

The PEL duration \( T_0 \) (in hr) of exposing to a noise of SPL (in dB(A)) can be calculated by using an exchange rate of 5 dB [4,15]:

\[ T_0 = \frac{8}{2^{(\text{SPL} - 90)/5}} \]  
(11)
For example, the PEL duration $T_O$ for exposing to an environment of 95 dB(A) is $8/2^{(95-90)/5}$ or 4 hrs. Similarly, PEL duration $T_O$ for an environment of 120 dB(A) would only be 1/8 hr or 7.5 mins. In short, for every 5 dB increase in the noise exposure to the worker, the exposure duration to PEL is cut to half.

- ACGIH Standards [15,16]

An 8-hr criteria level of 85 dB(A) was proposed by the ACGIH. This is different from the 90 dB(A) in OSHA. The TLV duration $T_A$ (in hr) for any given noise level SPL (in dB(A)) can be calculated based on the equal energy rule, i.e. an exchange rate of 3 dB:

$$T_A = \frac{8}{2^{(SPL-85)/3}} \tag{12}$$

In comparing with OSHA, PEL duration $T_A$ for an environment of 95 dB(A) is only 0.79 hr; and $T_A$ for 120 dB(A) is only about 9 s. Therefore, ACGIH is much tighter in controlling the PEL duration.

The PEL is taken to be 90 dB(A) in many countries including the European Community. Though, other values are used in other countries such as 87 dB(A) in Canada, 70 to 90 in China, and 85 or 90 in UK [4]. There is a worldwide trend to reduce the daily exposure level to 85 dB(A), which is taken as an informal preferred value.

8. **RECOMMENDATION ON TAKING THE EXCHANGE RATE OF 3 dB, 5 dB or 6 dB?**

Comparison of the SPL with the allowed exposure time at different exchange rates of 3 dB, 5 dB and 6 dB is shown in Fig. 3. There is a 4 dB difference for reducing the exposure time by 1/4 for the two different exchange rates at 3 dB and 5 dB. This gives a 6 dB difference for the same reduction in exposure time, while comparing the exchange rate of 3 dB with 6 dB.

As the exposure time is further reduced by half, the difference of the change in the SPL for these two exchange rates increases, say up to 10 dB difference for reducing the exposure time by 1/32 for using the exchange rates of 3 dB and 5 dB. The difference is up to 15 dB for the exchange rates of 3 dB and 6 dB.

Starting from the same initial SPL, say the first action level at 85 dB(A), by reducing the exposure time from 8 hrs to 0.25 hr (i.e. 15 mins), an exchange rate of 5 dB allows an increase of SPL to 110 dB(A), i.e. 25 dB allowance. However, for an exchange rate of 3 dB, only 15 dB of increase is allowed to reach 100 dB(A). If the exchange rate is 6 dB, an increase of SPL to 115 dB(A) will be allowed!

![Fig. 3: Comparison of different exchange rates](image-url)
9. CONCLUSION

The physical principle behind using the exchange rate of 3 dB in the local FIU code [1,2] is reviewed. This value was worked out based on the “equal energy rule” [3,6,7]. Other exchange rate values of 5 dB and 6 dB are illustrated. The exchange rate is very important as it will affect the maximum allowed SPL of the noise and the duration of exposure.

As demonstrated in this paper, a smaller exchange rate will reduce the maximum allowed SPL significantly. But it might not be necessary to use a smaller exchange rate as the health effects to local citizens are not yet clear. Empirical data on human response to noise was measured in elsewhere [e.g. 11,12], not measured under local conditions. The noise background of local work places, living styles of local citizens and working customs of local labours are entirely different from those overseas. Acoustic data on health effects must be explored before setting up workable regulations. Further studies should be carried out to support the reasons for adopting any exchange rate, say 3 dB as in the FIU code [1,2], in Hong Kong.

REFERENCES

1. Factories and Industrial Undertakings (Noise at Work) Regulation, Labour Department, Hong Kong Special Administrative Region, February (2000).
APPENDIX A: EXCHANGE RATE OF 3 dB

Defining $L_{\text{Eq}(1)}$ and $L_{\text{Eq}(2)}$ as in equation (1):

$$L_{\text{Eq}(1)} = 10 \log_{10} \left( \frac{1}{t_1} \int_0^{t_1} \left( \frac{P_1}{P_0} \right)^2 \, dt \right)$$  \hspace{1cm} (A1)

and

$$L_{\text{Eq}(2)} = 10 \log_{10} \left( \frac{1}{t_2} \int_0^{t_2} \left( \frac{P_2}{P_0} \right)^2 \, dt \right)$$ \hspace{1cm} (A2)

Equations (4), (A1) and (A2) give:

$$\frac{t_2}{t_1} = 10^{\frac{\text{LEq}(2) - \text{LEq}(1)}{60}}$$ \hspace{1cm} (A3)

By taking $P_1$ and $P_2$ as constant values in equation (4) gives:

$$t_1 P_1^2 = t_2 P_2^2$$ \hspace{1cm} (A4)

This gives $t_2$ of $4t_1$ if $P_2$ is 0.5 $P_1$, and

$$L_{\text{Eq}(1)} - L_{\text{Eq}(2)} = 10 \log_{10} \left( \frac{1}{t_1} \int_0^{t_1} \left( \frac{P_1}{P_0} \right)^2 \, dt \right) - 10 \log_{10} \left( \frac{1}{t_2} \int_0^{t_2} \left( \frac{P_2}{P_0} \right)^2 \, dt \right)$$

Equation (4) gives the following difference of $L_{\text{Eq}(1)}$ and $L_{\text{Eq}(2)}$ for doubling the exposure time, say taking $t_2 = 2t_1$:

$$L_{\text{Eq}(1)} - L_{\text{Eq}(2)} = 10 \log_{10} \left( \frac{1}{t_1} \int_0^{t_1} \left( \frac{P_1}{P_0} \right)^2 \, dt \right) - 10 \log_{10} \left( \frac{1}{2t_1} \int_0^{t_1} \left( \frac{P_1}{P_0} \right)^2 \, dt \right)$$

$$= 10 \log_{10} \left( \frac{1}{t_1} \int_0^{t_1} \left( \frac{P_1}{P_0} \right)^2 \, dt \right) - 10 \log_{10} \left( \frac{1}{2t_1} \int_0^{t_1} \left( \frac{P_1}{P_0} \right)^2 \, dt \right) + 10 \log_{10}(2)$$

$$= 10 \log_{10}(2)$$

$$= 3 \text{ dB}$$

APPENDIX B: EXCHANGE RATE OF 6 dB

Again, using equation (1):

$$L_{\text{Eq}(1)} - L_{\text{Eq}(2)}$$

$$= 10 \log_{10} \left( \frac{1}{t_1} \int_0^{t_1} \left( \frac{P_1}{P_0} \right)^2 \, dt \right) - 10 \log_{10} \left( \frac{1}{t_2} \int_0^{t_2} \left( \frac{P_2}{P_0} \right)^2 \, dt \right)$$  \hspace{1cm} (B1)

Assume $P_1$ and $P_2$ to be constant values:

$$L_{\text{Eq}(1)} - L_{\text{Eq}(2)} = 10 \log_{10} \left( \frac{P_1^2}{P_0^2} \right) - 10 \log_{10} \left( \frac{P_2^2}{P_0^2} \right)$$

$$= 10 \log_{10} \left( \frac{P_1^2}{P_0^2} \right) - 10 \log_{10} \left( \frac{P_2^2}{P_0^2} \right)$$

$$= 10 \log_{10} \left( \frac{P_1^2}{P_0^2} \right) - 10 \log_{10} \left( \frac{P_1^2}{2P_0^2} \right)$$

$$= 10 \log_{10} \left( \frac{P_1^2}{P_0^2} \right) - 10 \log_{10} \left( \frac{P_1^2}{4P_0^2} \right)$$

$$= 10 \log_{10} \left( \frac{P_1^2}{P_0^2} \right) - 10 \log_{10} \left( \frac{P_1^2}{4P_0^2} \right) + 10 \log_{10}(4)$$

$$= 6 \text{ dB}$$