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ON LEVEL LIMITS FOR HEARING PROTECTION

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INTRODUCTION

The most important function of the auditory sense is the frequency analysis that allows to resolve complex sounds into their component frequencies. The mechano-electrical energy transduction system that initiates the filtering action in the internal ear is a very complicated and not well known process. Its sharpness asks for a secondary neuronal filter action in the cochlear micromechanism based on an active function of the hair cells (Evans, 1986). The filtering action in the cochlea is physiologically vulnerable. In any case, the deterioration of the filtering action and, consequently, of the auditory function, is related to the degradation of the hair cells, in particular the outer ones. Figure 1, after Evans and Harrison (1976), shows the correlation between the loss in sharpness of the Frequency Threshold Curves (FTC), in the high frequency range, and the proportion of inner (IHC) and outer hair cells (OHC) remaining in the cochlea of a guinea pig ear damaged with kanamycin.

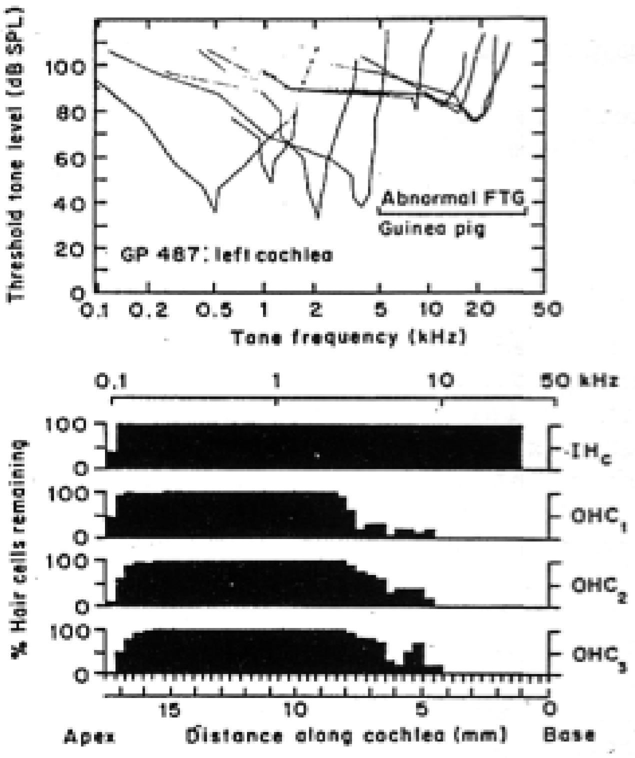


Fig. 1

Among other causes, overexposure to mechanical vibrations of the organ of Corty due to intense noise has shown to alter the integrity of the hair cells.

Industrial environments being one of the most common places where people are exposed to intense noise levels ask for regulations and legislation to protect their health including physiological and psychical effects and , in particular , the auditory preservation.

In this conference, we analyze the correlation between the physical parameters of noise exposure (level, spectra and time pattern), with hearing damage as related to the adoption of protective noise limits.

AUDITORY IMPAIRMENT AND HANDICAP

The American Academy of Otorinolaringology defined the Auditory Handicap as "an impairment sufficient to affect a person's efficiency in the activities of daily living". In order to simplify this broad concept, it has been adopted as a realistic practice to relate handicap with ordinary speech inteligibility, mainly because the detereoration of the cochlear analitical function fails to recognice spectral complex sounds like speech consonants. A further simplification is added by evaluating speech inteligibility in terms of tonal audiometry.

The impairment is measured in Hearing Level decibels relative to the Standard Hearing Threshold at specified audiometric frequencies (500-4000 Hz). The shift in threshold caused by a sound exposure being permanent (PTS) or temporary (TTS) according to recovery with time after exposure.

The Handicap is defined in terms of the difference between the individual permanent hearing level and the "low fence", an empirical curve that, theoretically, marks the limit between "no difficulty" and "some difficulty" in understanding ordinary speech, a line of relative fiability to relate tonal audiometry with speech understanding (Noble, 1978).

Damage Risk

The damage risk to a sound exposure is defined in percentage of the average hearing impairment difference between exposed and non exposed comparable populations.

When evaluating the hearing impairment due to a definite sound exposure, as in the case of industrial environments, other concurrent factors must be eliminated:

Presbycusis, or age action;

Sociocusis, sound exposure aside from the industrial environment, as in everyday life, and

Nosoacusis, other otological damaging factors such as chemicals, drugs, diseases, etc.

The noise induced hearing impairment is then referred as NIPTS or NITTS. In the case of industrial noise, these abbreviations are preceded by an I (INIPTS or INITTS).

Damage Criteria

With reference to the noise or sound induced handicap, a first step is to define the zero reference of hearing damage. There is a generical concordance among different criteria in defining the Hearing Losses by the average of H.L. dB at three or four fixed frequencies (500 Hz, 1, 2 or even 3 or 4 kHz), the handicap starting at values ranging from 15 to 25 dB (viz. CHABA, 15 dB; ANSI, 25 dB; ISO, 25 dB; etc.). These losses are considered acceptable in relation to the mentioned empirical line of speech understanding.

A general remark to be made when trying to protect individuals from hearing impairment is that all limits and criteria are refered to the median level of the exposed population, i.e. the value that divides the population into two halves which are likely to have less or more losses than the limit value. Dangerous deviations from this value are mainly due to individual susceptibility to noise exposure, a problem that asks for screening tests to detect such persons.

As to the deviations encountered in epidemiological studies, we refer to Table I that reproduces values of 50, 20 and 10 percentiles as

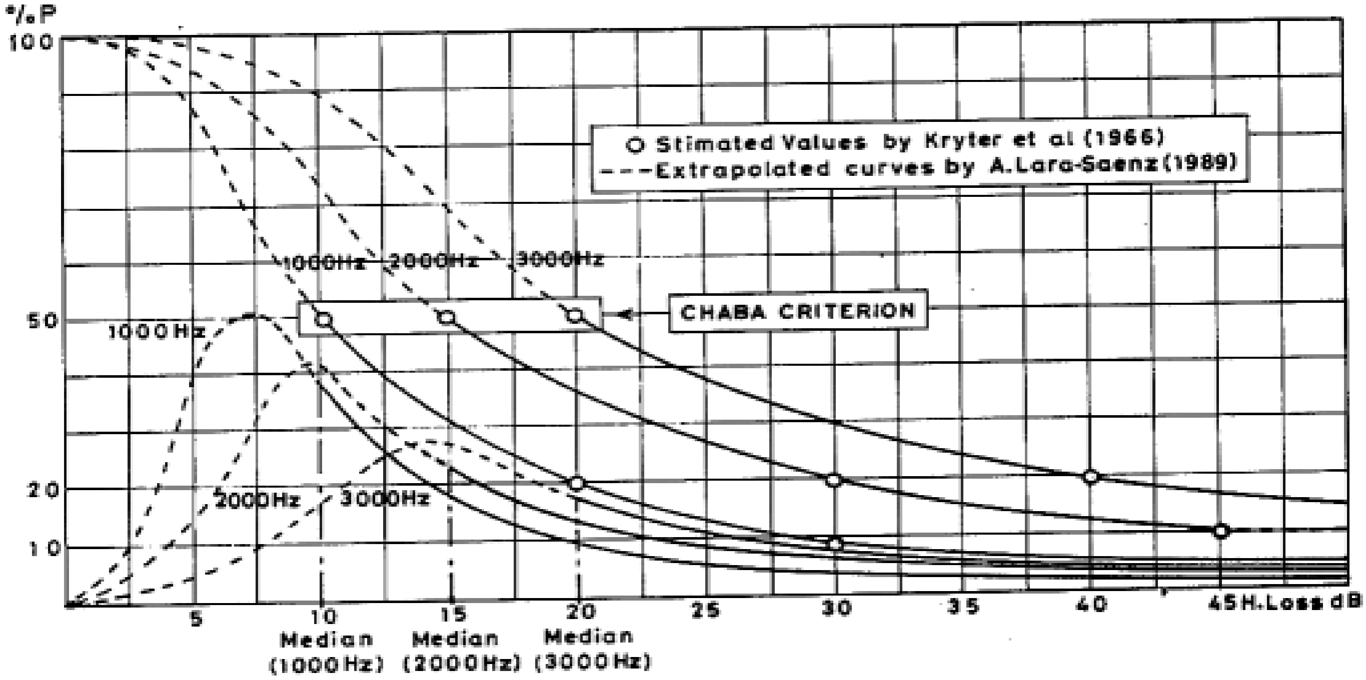


Fig.2

given by Kryter and Ward (1966) based on Glorig and Nixon (1961) and Rudmose (1957). The extrapolated curves of level distributions of figure 2 at 1000, 2000 and 3000 Hz, and the corresponding cumulative curves show an assymmetrical distribution with median value well separated from the modal and average values.

According to these data, it could be possible to find, after years of exposure, a 10% of people with 60 dB losses at 3000 Hz in an environment considered acceptable because 20 dB is the mean value!

TABLE I

Test frequency (Hz)	NIPTS(dB):Percentile 50%	20%	10%
1000	10	20	30
2000	15	30	45
3000	20	40	60

Once this important fact is taken into consideration, all hearing damage criteria are referred to the median value of the average population.

LIMITS FOR CONSTANT NOISE EXPOSURE

Data on INIPTS have to be retrospective, mainly based on hearing surveys in industries with steady and permanent noise levels.

Data on occupational deafness were collected by Stevens et al. (1953). The ASA Committee Z24-X2, analyzing industrial data, found several useful correlations as published in the report "The relations of Hearing Loss to Noise Exposure" (N.Y. 1954).

Some main findings in this field are quoted below:

-Hearing losses due to noise exposure (NE) tend to be maxima in the range 3-6 kHz for any given exposure. (A maximum at 4 kHz can generally be due to noise exposure)

-For speech understanding, only hearing losses in the range 0.5-2 kHz are important.

-Hearing losses below 500 Hz are generally less or equal to those at 500 Hz, but hearing losses above 2000 Hz may be greater than the loss at 2 kHz.

-Individual susceptibility is reflected in losses above 2 kHz.

-Hearing loss is not an image of the noise spectrum.

-In the noise spectrum, it can be selected an octave band (sorting octave) that correlates better with the Hearing Losses.

-Noise levels below 1000 Hz are more important as regards to speech losses.

-Distribution of Hearing Losses in populations exposed to noise have a greater spread than for non-exposed populations. (This fact is important in evaluating data from World's Fair).

The survey by Passchier-Vermeer (1968) is considered a representative one of INIPTS in workers exposed 8 hours per day for years, with a good linear regression with levels in dBA, or with NR curves, or even with the integral of the noise pressure (Kraak, 1979).

Because of simplicity besides reliability, levels in dBA have been thorougly adopted to stablish limits of sound exposure.

The refered survey includes the INIPTS as a function of the frequency for 10 or more years of exposure to constant noise levels in dBA, the regression curves being also linear but with different slopes and values (Fig. 3).

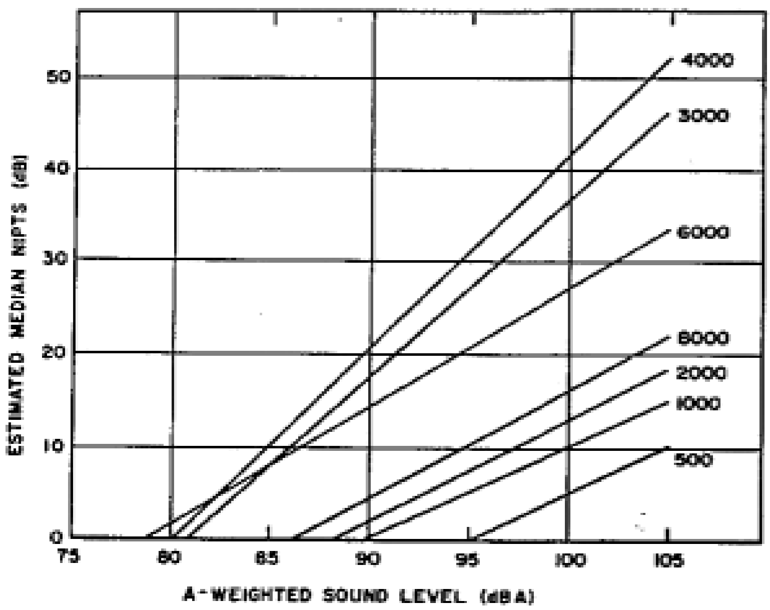


Fig. 3

It can be seen the higher ear liablity to high frequencies, and how the frequencies related with speech intelligibility (500, 1000, 2000 Hz) are only affected by levels above 90 dBA. This fact legitimates the previously referred value of the damage criteria for handicap.

It is seen also that 80 dBA is a low value and 85 dBA an acceptable one, as it may produce less than 10 dB and only at the higher frequencies .

Nevertheless, it must be recalled that these values are <u>median estimated</u> INIPTS and that significant individual deviations can be produced.

It may be then concluded that values ranking from 85 to 90 dBA are reasonable limits for constant level noise exposure to a 8 hour/day, for 10 or more years.

LIMITS FOR TIME VARYING NOISE LEVELS EXPOSURE

INIPTS corresponding to exposure to high levels of time varying patterns of noise are almost inexistent or very incomplete. Real tests ask for laboratory work, where controlled noise levels and time patterns can be obtained to carry out experiments to determine Transitory

Threshold Shifts. Laboratory experiments with intermittent high levels are only made with animals . The additional problem is to extrapolate from TTS to PTS and from animals to persons.

Growth And Recovery Of TTS: CHABA Damage Risk Criteria

The CHABA (Committee on Hearing, Bioacoustics and Biomechanics of the USA National Academy of Sciences) proposed in 1966 a set of contour curves of Damage Risk Criteria (DRC) for continuous and intermittent exposures to steady noise (Kryter et al., 1966, Ward, 1970) based on the three main following assumptions:

a) a NE pattern would be considered acceptable if it produces in the average worker no more than 10 dB of PTS at 1 kHz or below, 15 dB at 2 kHz or 20 dB at 3 kHz and above.

b) The PTS after 10 or more years of NE will not exceed the TTS_2 generated by a single day exposure. (For simplicity, it was assumed that they are equal).

c) All exposures that produce a given TTS_2 will be equally hazardous.

By using data on TTS, including intensive laboratory tests, the following main findings were used to derive the CHABA DRC:

1- In daily exposure, recovery from temporary threshold shifts in less than 16 hours will not produce an accumulative effect resulting in a PTS.

2- Recovery curves have shown that TTS_2, i.e., the threshold shift measured 2 minutes after the cessation of the exposure to noise, is a good indication of the TTS induced by any particular noise exposure. Some other recovery times (30 or 50 minutes) have been proposed, but TTS_2 behaves in most cases as a significant index.

TTS FOR INTERMITTENT NOISE

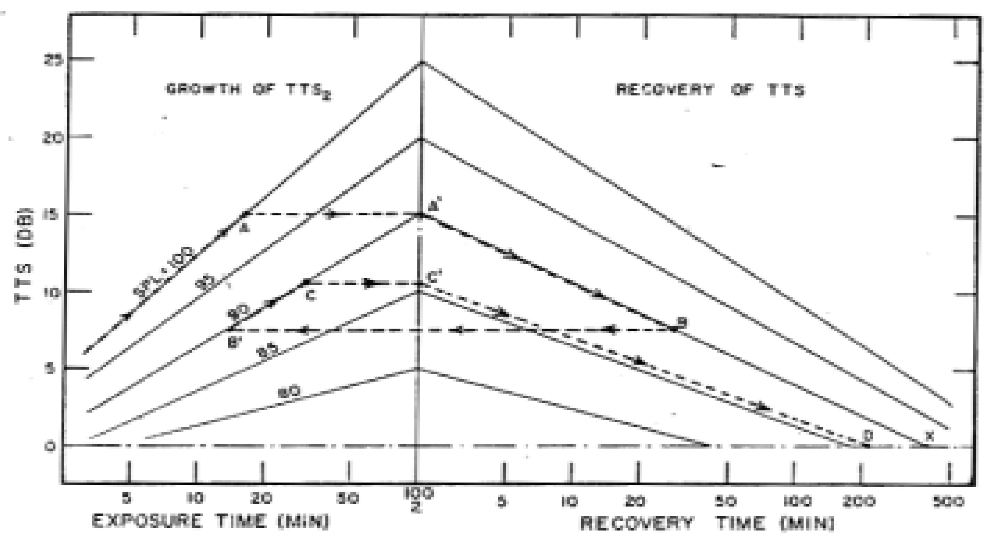


Fig. 4

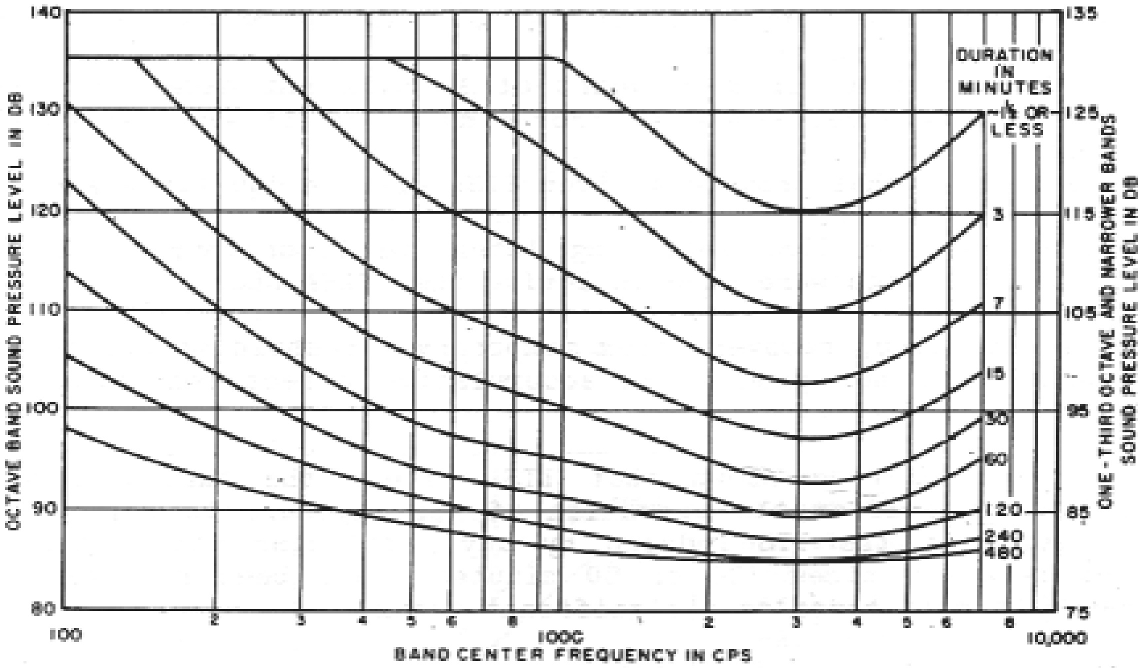
3- The growth and recovery of TTS_2 are exponential (Fig. 4; Ward, 1970).

4- For a constant NE level, an asymptotic value of TTS_2 is reached in 8 to 12 hours.

5- The growth of TTS_2 with NE level is approximately linear, once this has reached some SPL defined as "effective quiet". (About 75 dB in octave bands). Below this value, not significant TTS_2 are shown (The effective quiet is frequency independent, but the growths of TTS_2 increase with frequency).

Levels above effective quiet are referred as Effective level (EL).(Ward el al., 1976). Consequently, a 95 dB constant NE (EL= 20 dB) will produce twice as much TTS_2 as one of 85 dB (EL= 10 dB).

Using all these findings and selecting average curves (Fig.4) for the growth and recovery of TTS_2 CHABA damage risk contours for steady NE give the limit levels in dB of SPL in octave and 1/3 octave noise bands not to be exceeded in 10 or more years for single exposures ranging from 8 hours down to half a minute or less. (Fig. 5, Kryter et al., 1966).



Fig, 5

Broad band noise follows the criteria of the highest band reaching the contours. If more bands exceed the contours, the hearing loss will cover wider range of frequencies, every region being more affected by a band of approximately half an octave below.

For intermittent noise level exposures, the influence of the exposure time in the CHABA contours and interval values are mainly based on the finding that for fluctuating level or rapid interruptions (less than 5 minutes) the TTS_2 is proportional to the arithmetic average of the EL. (The same TTS will be generated by 8 hours of NE to 85 dB that 4 hours to 95 dB or by a random fluctuating noise with an average of 10 dB over 75 dB).

This criterion, as compared with the total energy theory (increase of 3 dB for each halving of time), admits greater increase in levels when reducing the exposure time. A level of 95 dB acting alternatively in equal "on" and "off" periods will generate the same TTS_2 than a continuous one of 75+(95-75/2)= 85 dB, i.e. a difference of 10 dB, instead of 3 dB!.

Furthermore, the difference between both criteria varies with the ratio of "on time" to the "on plus off time", called the on-fraction rule (Ward, 1970).

Total inmission theory by Robinson (1966), associates hazard with the total A weighted energy, regardless of the time distribution for the whole working week. It is an extension of the total energy theory, based only on data of continuous exposure surveys.

<u>Short and large bursts of noise.</u>

Set of contours were established for short bursts of noise (less than 2 minutes) relating the total daily exposure time with SPL for different on-fractions and for different band centre frequency of the NE (Fig. 6). For a band centered at 1000 Hz and 1´ on-time burst with on-fraction 0.5´, the maximum level for 2 h of daily exposure will be 106 dB.

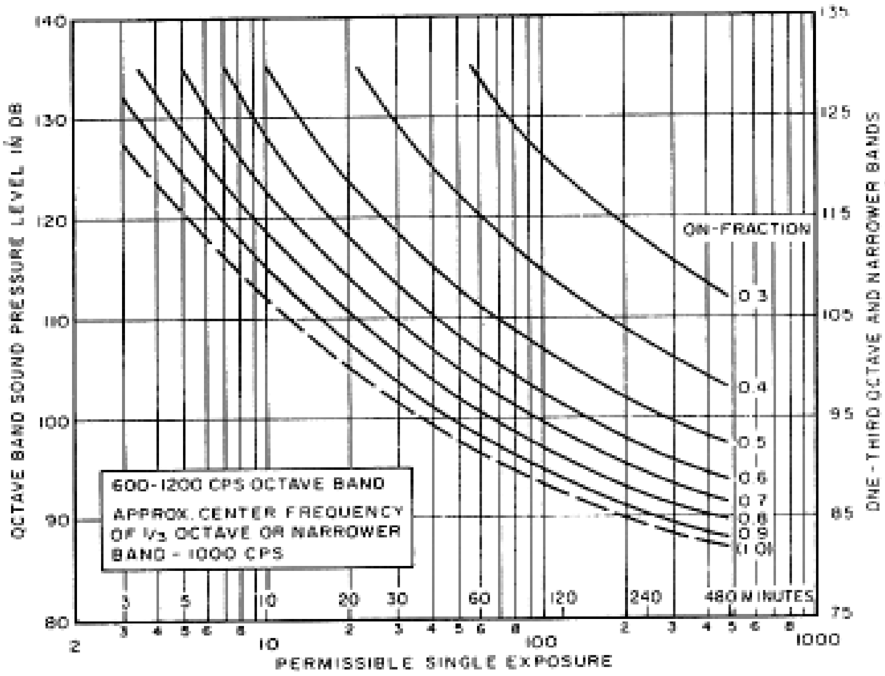


Fig. 6

For larger on-time bursts, the influence of growth and recovery times leads to another set of curves that relates noise burst duration with required recovery time for different frequency bands. (Fig. 7).

A 10´ on-time burst of an octave band of noise centered at 1000 Hz with a level of 106 dB, will require 15 minutes of recovery time between bursts, at a maximum level given by the limit for 8 h of continuous exposure (Fig. 5), i.e. 86 dB in this case.

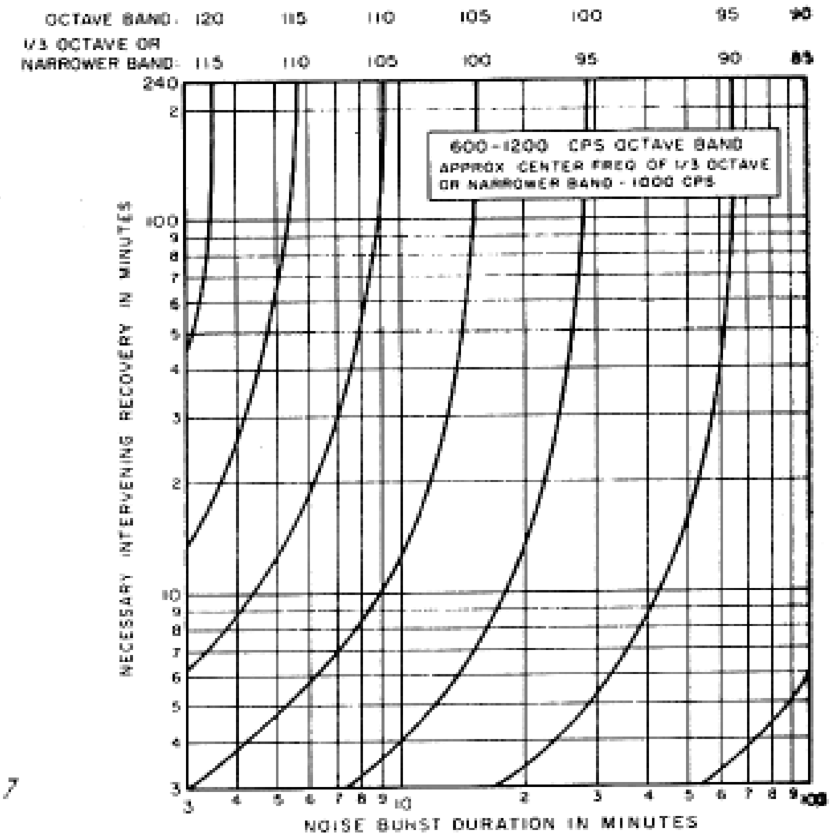


Fig. 7

Impulsive noise was not included, but evidence was noticed that repeated exposure to sound impulses over 140 dB (200 Pa) could produce in some persons significant hearing impairment.

The CHABA DRC contours had the merits of quantifying the influence of growth and recovery time of temporary shifts of hearing threshold and reasonably relate measurable daily TTS_2 with long term exposure PTS. For practical application, it has the difficulty of the measurement of levels in bands of frequency. A good simplification was introduced when there was evidence that the damage risk correlates well with the global level of the noise in dBA (It can be observed that the DRC contours for steady noise exposure, Fig. 5, approximate to the shape of the "A" curve). On this basis, it was given the simplified Table II of maximum values in dBA as a function both of total time of exposure and number of intervals.

TABLE II

Exposure time	No. of intervals of exposure in 8 hours						
	1	3	7	15	35	75	150
8 h	90	-	-	-	-	-	-
6 h	91	92	93	94	94	94	94
4 h	93	94	95	96	98	99	100
2 h	96	98	100	103	106	109	112
1 h	99	102	105	109	114	-	-
30 '	102	105	110	114	-	-	-
15 '	105	110	115	-	-	-	-
8 '	108	115	-	-	-	-	-
4 '	111	-	-	-	-	-	-

ISO STANDARD

The ISO Standard 1999 (1975) "Assesment of occupational noise exposure for hearing conservation purposes" is based on the total energy concept, assuming no handicap for a hearing loss of 25 dB (arithmetic mean of PTS at 500, 1000 and 2000 Hz).

Partial indices E_i of noise exposure are given to weekly exposures Δti at different levels L_i, (dBA), by the expression

$$E_i = \Delta\, ti/40\ 10^{L_i-70/10}$$

the composite index being $E_c = \Sigma\, E_i$, and its relation with the equivalent continuous level $L_{eq} = 70 + 10\ \lg E_c$.

A table (ISO, 1999) gives the percentage of damage risk for L_{eq} from 80 to 115 dBA and 5 to 45 years of daily exposure.

TRESHOLD LIMIT VALUE

A further simplification was introduced by the NIOSH (National Institute for Occupational Safety and Health) of USA for the TLV (Threshold Limit Value) as a function of exposure time, deduced from the expression

$$T_{max} = \frac{16}{2^{(L-80)/5}}$$

For intermittent daily exposure (T_i) at different levels (L_i), the additional condition being

$$\Sigma \frac{T_i}{(T_{max})_i} \leq 1$$

This criterion also admits higher values that the equal energy, viz. 5 dBA instead 3 dBA for each halving the time. It was adopted in USA in 1971, being later corrected the formula for 85 instead of 80 dBA. (Walsh-Healey Act, Anon 1969).

For impulsive noise (peaks at intervals larger than 1 minute), the following Table includes number of impulses per day as a function of the peak level.

TABLE III (NIOSH)

dB	Impulses/day
140	100
130	1.000
120	10.000

<u>EEC DIRECTIVE 86/188</u>

Not to be exhaustive, we conclude with the Directive that the Council of the EEC has published in 1986, after several years of harmonization work, to protect the workers from hearing impairment derived from noise exposure in working environments.

The Directive refers all rules and recommendations to the daily equivalent personal noise exposure level in dBA, L_{EPd} given by

$$L_{EP,d} = 10 \log \left| \frac{1}{T_e} \int_0^{T_e} \frac{p_A^2}{p_o^2} \right| + 10 \log \frac{T_e}{T_o} =$$

$$= L_{Aeq,T_e} + 10 \log \frac{T_e}{T_o} = 10 \log \left| \sum_{i=1}^{m} 10^{(L_A)_i/10} \right| + 10 \log \frac{T_e}{T_o}$$

where p_A = instant value of the acoustic pressure with "A" weighting
p_o = cero reference acoustic pressure: 20 µPa
T_e = daily exposure time
T_o = reference daily exposure time; 8 hours
$(L_A)_i$ = constant noise level during period T_i

For *n* weekly working days, the weekly equivalent personal noise exposure is

$$L_{EP,W} = 10 \log \left| \frac{1}{n} \sum_{1}^{n} 10^{(L_{EP,d})_n/10} \right|$$

All regulations and recommendations are referred to the value of L_{EPd}, the most significatives being:

- For $L_{EPd} \geq$ 85 dBA or $p_{inst} \geq$ 200 Pa(L= 140 dB), workers must be informed of the situation (Art 4th) and ear protectors must be made available (Art 6th).
- If $L_{EPd} \geq$ 90 dBA, noisy areas must be signalized, causes must be investigated, control programmes established (Art 5th) and the use of ear protectors is obligatory (Art 6th).

CONCLUSIONS

- It is not possible to define absolute safe limits for noise exposure in the broad sense that everybody will be protected. Limit values are referred to median values of the average populations. Strong deviations from the median are due to personal susceptibility, what calls for previous specialized screening tests.

- Limits for continuous steady noise exposure are reasonably well founded in available epidemiological data on INIPTS, including estimated evaluations on Presbicusis, Noso and Socioacusis. These limits are also in good agreement with those derived from laboratory TTS experiments.

- The total energy concept applies relatively well when comparing continuous steady exposure of different duration. For intermittent or fluctuating levels the limits are too conservative as compared with the temporal theory (CHABA) because of the ability of the hearing mechanisms to recover from TTS, at least for bursts shorter than 5 minutes. (For longer bursts CHABA curves separate from later evidence, that recovery from repeated exposure follows quasi-paralel lines instead of convergent ones (Fig 4) i.e., recovery becomes longer along the daily exposure).

- The relationship between temporary and permanent effects of noise exposure is far from being well known, as to define safe limits mainly for intermittent and fluctuating noise exposure.

- The CEE Directive follows the total energy criterion with reasonable level limits, feasible applicability and relatively easy evaluation with present noise measurement equipment.

- More research is needed both in relating PTS with TTS and to extrapolate from experiments with animals to man reactions.

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