Human temporary threshold shift (TTS) and damage risk

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Information regarding the relation of human temporary threshold shift (TTS) to properties of steady-state and intermittent noise published since the 1966 appearance of the CHABA damage risk contours is reviewed. The review focuses on results from four investigative areas relevant to potential revision of the CHABA contours including effects of long-duration exposure and asymptotic threshold shifts (ATS); equivalent quiet and /or safe noise levels; effects of intermittency; and use of noise-induced temporary threshold shift (NITTS) to predict susceptibility to noise-induced permanent threshold shift (NIPTS). These data indicate that two of three major postulates on which the original contours were based are not valid. First, recovery from TTS is not independent of the conditions that produced the TTS as was assumed. Second, the assumption that all exposures that produce equal TTS_2 are equally hazardous is not substantiated. The third postulate was that NIPTS produced by 10 years of daily exposure is approximately equal to the TTS_2 produced by the same noise after an 8-h exposure. Based upon several TTS experiments showing that TTS reaches an asymptote after about 8 h of exposure, the third CHABA postulate can be reworded to state the hypothesis that ATS produced by sound of fixed level and spectrum represents an upper bound on PTS produced by that sound regardless of the exposure duration or the number of times exposed. This hypothesis has a strong, logical foundation if ATS represents a true asymptote for TTS, not a temporary plateau, and if threshold shifts do not increase after the noise exposure ceases.

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INTRODUCTION

Recognized as a milestone in predicting the hazard of noise to hearing, the damage risk contours published by CHABA (Kryter *et al.*, 1966), were developed using data both from field studies of permanent hearing loss measured in industrial workers and from laboratory studies of temporary threshold shift (TTS). The published contours represent an approximation, arrived at indirectly from data that were acknowledged to be inadequate. Information regarding the relation of spectral variation, level, duration, repetition rate, and other physical properties of noise to hearing loss came from studies of TTS under controlled laboratory conditions. The relations between noise-induced permanent threshold shift (NIPTS) and TTS was not then, and is not now, precisely known.

Gaps in the information available required major assumptions regarding TTS by the working group that developed the contours. These assumptions were framed in the form of the following three postulates that served as the foundation for this effort.

(1) The temporary threshold shift 2 min after the end of the exposure (TTS_2) will rank the effects of the exposure in the same way as would TTS measured at some longer time interval following the exposure. Recovery from TTS does not depend on how the TTS_2 was produced.

(2) All exposures that produce equal TTS_2 are equally hazardous.

(3) The noise-induced permanent threshold shift (NIPTS) produced by ten years of daily exposure to a given pattern of noise is approximately equal to the TTS_2 produced by the same noise after an 8-h exposure.

The working group recognized the lack of direct support for these postulates but felt that the postulates represented the best engineering approximation to the information that was available. Because of the absence of support, the working group specifically recommended that the postulates be reviewed periodically.

In the two intervening decades between publication of the CHABA damage risk contours and now, there have been an impressive number of publications that were concerned with human TTS, either as a dependent or an independent variable. The interest in TTS research, particularly directed toward defining relations of TTS to physical properties of the sound exposure, seemed to plateau in the decade of the 1970s and has been declining since. This decrease in investigative activity is evidenced by the reduction in relevant publications and by an apparent decrement in research support. This decline seems to parallel the cooling of interest in federal regulatory involvement particularly in noxious effects of noise. In this era of protection of research subjects, both human and laboratory animals, the problems associated with obtaining institutional approval for this type of research undoubtedly makes studies of TTS less attractive.

As indicated in the title, this is a review of information regarding human TTS that has appeared since the 1966 publication of the CHABA damage risk contours. Effects of impulsive and impact noise will not be considered here. Nor will investigations that used lower forms of laboratory animals or that were interested in NIPTS be discussed. These

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important topics will be treated elsewhere. This review is not intended to be exhaustive. Rather, the presentation will focus on results from four investigative areas that are particularly relevant to potential revision of the CHABA contours. These investigative areas include: (1) effects of exposures of long duration and asymptotic threshold shift (ATS); (2) equivalent quiet and/or safe levels; (3) effect of intermittency of noise exposure; and (4) use of NITTS to predict susceptibility to NIPTS.

I. LONG-DURATION EXPOSURE

Prior to 1970, most of the TTS data for human subjects came from studies where the duration of the exposure ranged from a few minutes to a few hours. Since that time, a number of investigations have been reported where the duration of exposure was relatively longer, ranging from 16–48 h (Mills *et al.*, 1970; Mosko *et al.*, 1970; Melnick, 1974, 1975, 1976; Melnick and Maves, 1974; Nixon *et al.*, 1975; Ward, 1975; Mills *et al.*, 1979, 1983). Mills *et al.* (1979) synthesized the results from their study of ATS from octave bands of noise centered at 0.5, 1.0, 2.0, and 4.0 kHz with data from similar earlier investigations. When the exposures are to sound levels which produce 30-dB ATS or less, the results demonstrate consistency. The frequencies at which the maximum effect of long-duration exposures occur depend on the spectrum of the noise. The maximum shift is observed at frequencies about 1/2 oct above the center frequency of the octave band, a familiar result in TTS experiments. This relation does not seem to hold when the octave bands of noise are below 500 Hz. Exposures to octave bands centered at 63, 125, and 250 Hz produced the maximum effect in the frequency range 300–750 Hz regardless of the center frequency of the exposure (Mills *et al.*, 1983).

The relation between threshold shifts in the frequency region of largest change and exposure duration can be described by a simple exponential function as shown in Fig. 1 taken from Mills *et al.* (1979). In this figure, Mills and his colleagues graphed their data together with those from four other sources (Mills *et al.*, 1970; Melnick, 1976; Ward, 1976; and Barry, 1976). To normalize the data for noise of different spectra and levels, growth and decay of threshold shifts are plotted as percent change where 100% is taken to be the asymptotic threshold shift. The agreement between the several sets of data is remarkable. The growth of TTS as a function of exposure time does not seem to be affected by the center frequency of the bands of noise, but is apparently applicable for most of the human auditory range. The limitation of this mathematical description is that, in humans, it may only apply to situations where ATS is 30 dB or less. Mills *et al.* (1979) present data for an 88-dB exposure to an octave band of noise centered at 4 kHz, which indicated a rapid increase in threshold shift after only 1 h of exposure and shifts of greater magnitude than would have been expected based on results from lesser noise levels. The exponential function of Fig. 1, and models of TTS with fixed time constants may have a restricted range of application.

ATS as represented by threshold shifts measured 2–8 min post-exposure demonstrates a systematic relationship to the octave band level of the noise exposure at least for the range of ATS less than 30 dB (Mills *et al.*, 1979). The relations are robust apparently appropriate for much of the auditory frequency range (0.5–4.0 kHz) and applicable to data from three species, human, chinchilla, and monkey. Figure 2 is a plot of ATS for the maximally affected frequencies as a function of the octave band SPL (OBL) of a noise centered at 4.0 kHz. The data are described well by two equations. For an ATS more than 8 dB, the equation

$$\mathrm{ATS} = 1.7(\mathrm{OBL} - C)$$

fits the observed relation. The subtractive constant C is determined by a linear extrapolation to the intercept and varies as a function of frequency and subject species. The constant C has been estimated for humans to be 74 dB SPL for the octave band centered at 4 kHz, 78 dB at 2 kHz, and 82 dB for the octave bands centered at 1.0 and 0.5 kHz (Mills *et al.*, 1979). For broadband noise the critical level has been calculated to be 78 dBA (Mills *et al.*, 1981).

While the linear equation is useful for describing the effect for ATS ranging from 8 to 30 dB and for estimating the beginning level for producing ATS represented by the con-

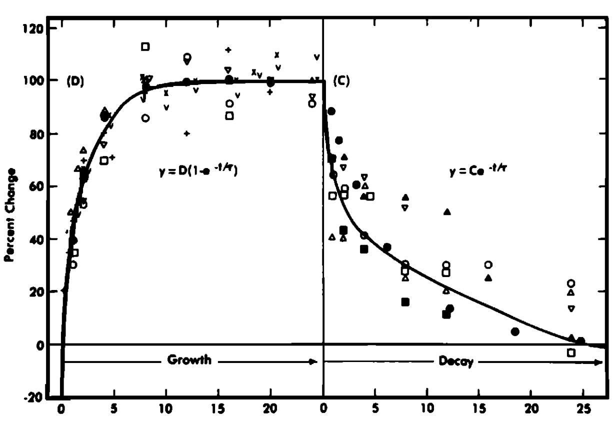

FIG. 1. Growth and decay of threshold shifts as percent change where the asymptotic thresholds shift equals 100%. Data taken from Mills *et al.* (1979); Melnick (1976); Ward (1976); and Barry (1976). Figure taken from Mills *et al.* (1979).

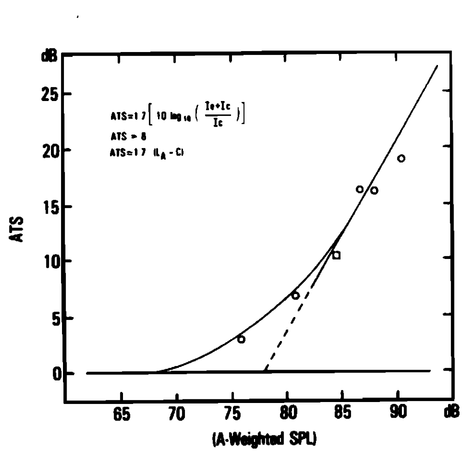

FIG. 2. The relation between asymptotic threshold shift (ATS) and the octave-band SPL of a noise centered at 4.0 kHz. Figure taken from Mills *et al.* (1981).

stant C, a curvilinear function provides a better fit to the data as a whole. For this curvilinear relationship, where 10 log Ie is equal to the octave band level of the exposure noise, SPL is equal to a constant C in 10 log C. Mills *et al.* give the equation

$$\text{ATS} = 1.7\ [10 \log_{10}(Ie + Ic/Ic)].$$

Recovery, under conditions of noise exposures of sufficient length to achieve ATS, can be prolonged and require as much as 48 h to return to pre-exposure hearing levels from threshold shifts in the 10-dB range (Melnick, 1976). When exposure durations are constant the decay of TTS is directly related to the level of the noise and therefore to the magnitude of TTS (Mills *et al.*, 1979). Johnson *et al.* (1976a) demonstrated that recovery from ATS depended on the amount of time noise exposure kept the person at the asymptotic levels of threshold shift. These investigators reported that recovery from a 48-h exposure was prolonged significantly when compared to recovery from a 24-h exposure despite the fact that the magnitude of the threshold shift was the same. Recovery from TTS depends on both the duration and the intensity of the noise exposure. TTS recovery is not related simply to the magnitude of the threshold shift as was assumed in the development of the CHABA damage risk contours.

While systematic relations between the acoustic variables of the exposure and ATS apply for the average of groups of subjects, the remarkable degree of individual variation observed for TTS and PTS continues to be the case for ATS as well. Standard deviations in ATS studies have been reported in the range of 6–9 dB, despite attempts to control for extraneous variables (Mills *et al.*, 1979; Melnick, 1976). The standard deviation was unaffected by the duration of exposure. The expected reduction in the intersubject variability as subjects achieved asymptotic threshold shift was not observed at least for durations as long as 24 h.

Individual differences in the pattern of TTS growth curves also can be significant. While TTS approached asymptotic levels systematically as a function of duration when the results are viewed for subjects as a group, when examined for individual subjects some reached asymptote in 1 h, while others required as much as 16 h (Melnick, 1974; Melnick and Maves, 1974; Mills *et al.*, 1979).

ATS data have particular relevance to establishing limits of noise exposure for prevention or minimizing noise-induced hearing loss. Mills *et al.* (1970) advanced the hypothesis that ATS produced by sound of fixed level and spectrum represents an upper bound on PTS produced by that sound regardless of the exposure duration or the number of times exposed. This hypothesis has a strong, logical foundation if ATS represents a true asymptote for TTS, not a temporary plateau, and if threshold shifts do not increase after the noise exposure ceases.

II. EQUIVALENT QUIET–SAFE LEVELS

The CHABA damage risk contours reflect the observation that exposure to noise conditions that were intermittent, where periods of noxious noise levels are interspersed with periods of quiet, were less hazardous to hearing. The likelihood of total quiet in the intervening intervals is remote. More appropriate for this application is the concept of "effective quiet," the highest sound-pressure level of a noise that will neither produce significant TTS nor retard recovery from TTS produced by a prior exposure to a higher noise level (Ward *et al.*, 1976). In the CHABA report effective quiet was defined as noise levels that fell below the octave band levels that could just be tolerated for an 8-h exposure, about 85 dB SPL or more depending on which octave band was involved. This definition was soon proven inadequate. Passchier-Vermeer (1973) observed that the experimental recovery curves used to derive the damage risk contours were established under quieter conditions and might not be valid where the level in the "off-periods" was as high as 85–90 dBA. She cited results from several studies in support of the criticism (Ward *et al.*, 1960; Lehnhardt and Bucking, 1968; Schwetz *et al.*, 1970; Klosterkotter, 1971).

Ward *et al.* (in their fundamental study reported in 1976) provided estimates of the upper intensity limits that qualify as effective quiet. These estimates, reported as octave band levels, are 77 dB SPL for the octave band centered at 0.25 kHz, 76 dB for the 0.5-kHz band, 69 dB for 1.0 kHz, 68 dB for 2.0 kHz and 65 dB for the octave band centered at 4.0 kHz. The estimates of Ward, *et al.* are significantly less than were assumed in the CHABA damage risk contours.

Levels identified as limits of effective quiet could serve as estimates of acoustic conditions safe as far as noise-induced hearing loss is concerned. Using the reasoning that some change in hearing sensitivity is physiologically normal, analagous to temporary changes in other sensory systems following stimulation, Ward *et al.* (1976) claimed that a requirement of no measurable TTS_2 following noise exposure is inappropriate to be considered the criterion for safe noise levels. These investigators make a strong argument for TTS_2 levels of 5 or even 10 dB being more acceptable. Octave band levels identified as effective quiet could be increased by 8 or 9 dB to produce a TTS_2 of 5 dB following an 8-h exposure to continuous noise.

Both studies of effective quiet and asymptotic threshold shifts provide data useful in estimating noise levels that present no hazard to hearing. Figure 3 graphs the effective quiet levels of Ward *et al.* (1976) as well as levels estimated to produce a TTS_2 of 5 dB. In addition, the critical levels calculated by Mills *et al.* (1979) are indicated. Recall that, when using the curvilinear fit for the ATS data, the levels calculated for the constant C from the linear equation produced about 5 dB of ATS. The agreement from these two different approaches provide remarkably similar estimates for safe noise levels. Further, when considering broadband noise exposures Ward *et al.* (1976) estimated the safe level to be 76 dBA, while Mills *et al.* (1981) identify this level as 78 dBA.

III. INTERMITTENT AND FLUCTUATING NOISE

Relating TTS to the physical properties of the fatiguing noise is considerably more complicated when the noise is intermittent or fluctuating rather than steady and continuous. In addition to the spectral properties of the noise and the duration of exposure, the temporal pattern of exposure influences the resulting changes in hearing sensitivity. The

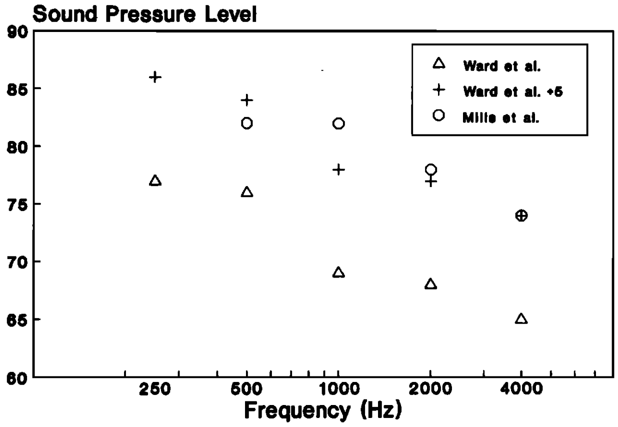

FIG. 3. Octave-Band sound-pressure levels identified as "effective quiet" and levels estimated to produce TTS_2 of 5 dB by Ward *et al.* (1976) shown together with estimates by Mills *et al.* (1979) of levels necessary to produce measureable asymptotic threshold shifts.

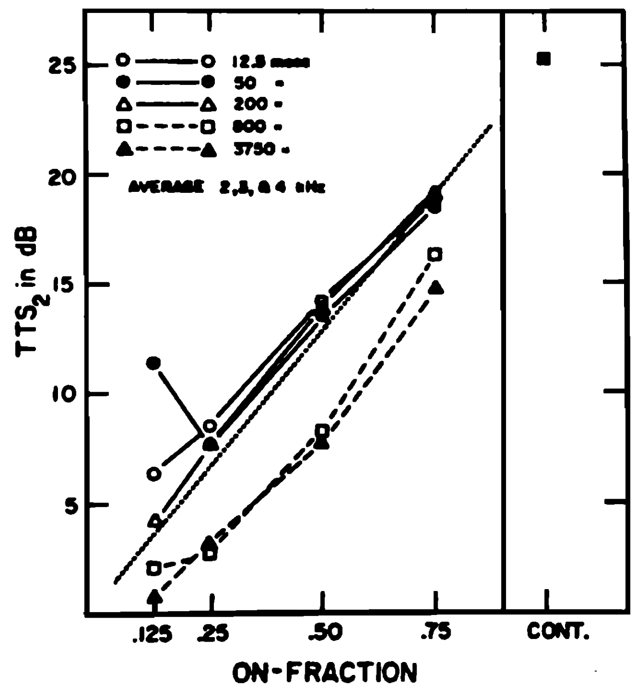

FIG. 4. Average temporary threshold shift at 2.0, 3.0, and 4.0 kHz as a function of noise on-fraction. The parameter is burst duration. The dotted line shows TTS predicted by the on-fraction rule. Figure is taken from Ahaus and Ward (1975).

major temporal variables for intermittent noises are the actual duration of the noise events (on time), the duration of the intervening periods of effective quiet (off time), and the overall interaction of the on and off times. As Ward noted in 1976, measuring the effect of these variables on TTS is staightforward. The difficulty arises in identifying unifying principles that simplify the complexity imposed by the almost infinite number of possible patterns of noise exposure that could occur. Although any particular noise exposure can be defined in the three-dimensional acoustic space involving frequency, level, and time, further simplification is needed for prediction of damage risk. The search for these unifying principles continues.

For a limited range of exposure conditions, TTS_2 is proportional to the ratio of the time occupied by the sound to the total exposure time. This reported relationship has been referred to as the "on fraction" rule. The on-fraction rule predicts that when the noise is on for half of the total period of exposure, the amount of TTS would be one-half of that which would have been produced if the noise had been continuous. Information from studies conducted in the early 1960s showed that the on-fraction seemed to describe the effects of repetitive sound sequences with noise burst durations ranging from 1.5 s to about 2 min for noises with energy primarily above 1200 Hz. For noise bursts longer than 2–3 min, more TTS would be measured than the on-fraction would predict (Selters and Ward, 1962; Ward, 1962). When most of the energy of a noise is below 1200 Hz, less TTS results than the on-fraction would predict. A low-frequency noise with an on-fraction of one-half, would result in 30% or less of the TTS produced by the noise if it were continuous.

In 1975, Ahaus and Ward observed that the on-fraction rule was appropriate for noise bursts less than 1 s. Using a two-octave band of noise (700–2800 Hz) at 114 dB SPL, they found that for on-fractions of 0.25 and greater the on-fraction rule correctly predicted TTS for burst durations of 200 ms or less. Exposures to noise with burst durations of 800 ms and 3.75 s, produced less TTS than predicted. These results are graphed in Fig. 4. The failure to support the on-fraction rule for the two longest burst times, particularly the 3.75-s duration was inconsistent with Ward's earlier data (1962). This discrepancy was attributed to the difference in spectra of the exposures. Ahaus and Ward included low-frequency energy in their two octave bands of noise, whereas the 1962 study found that the on-fraction rule only applied to octave band noises 1200–2400 Hz and 2400–4800 Hz. Less TTS was produced by octave bands of lower frequency. Ward attributed this reduction to attenuation of the lower frequencies by the reflex contraction of the middle ear muscles. Although the noise used by Ahaus and Ward contained frequencies up to 3000 Hz, it also contained significant energy at frequencies as low as 700 Hz. These investigators speculated that the middle-ear reflex was also involved in the reduction of TTS observed with their longer burst durations. Ahaus and Ward used the temporal characteristics of the aural reflex to explain deviation from the on-fraction rule for the 0.125 on-fraction, where for noise burst durations less than 200 ms, particularly 50 ms bursts, more TTS was measured than was predicted.

Not long after the CHABA damage risk contours were published (Kryter *et al.*, 1966), Ward (1970) identified at least two significant problems in the procedures used to calculate contours for intermittent noise exposure. To project the short-burst noise contours to octave-band levels greater than 100 dB at frequencies higher than 1 kHz, CHABA relied on extrapolation that was questionable. Ward observed in his study that any intermittent exposure to a 1400- to 2400-Hz octave band at 105 dB, using either short or long bursts, that produced 15 dB TTS_2 caused recovery to be prolonged (see Fig. 5). He concluded that if delayed recovery is an indication of impending hearing loss, then TTS_2

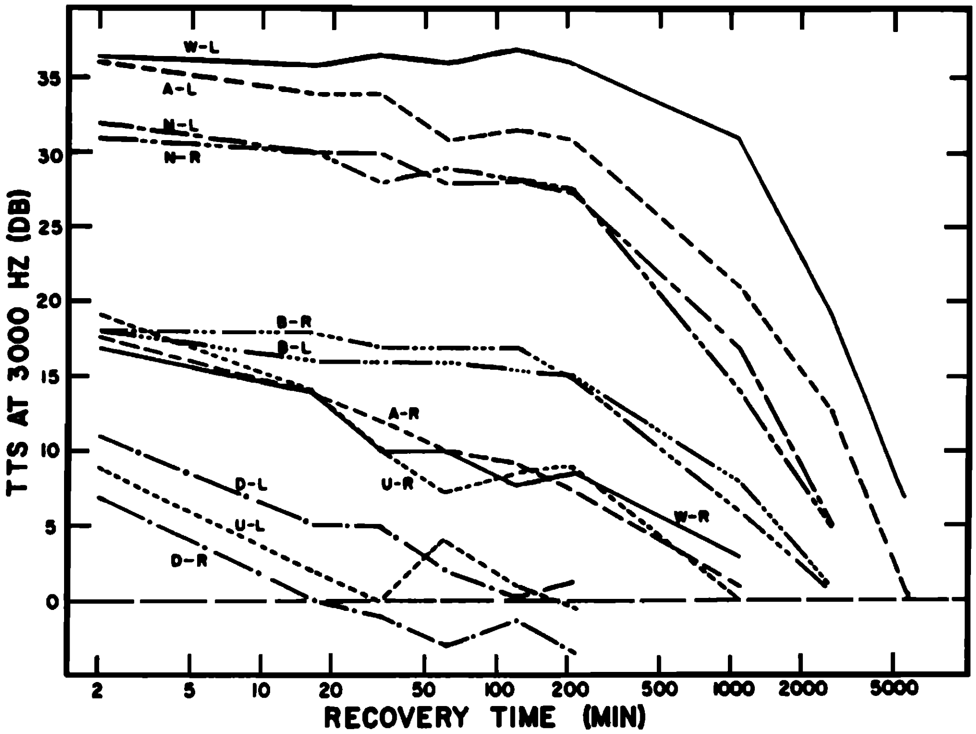

FIG. 5. Recovery from TTS at 3.0 kHz produced by 6-h intermittent exposure (3 s on, 7 s off) to a noise band 1.4–2.0 kHz at 105 dB SPL in 12 ears. Figure taken from Ward (1970).

following high-intensity, high-frequency intermittent noise is not a valid index of risk.

The second problem was identified in the iterative procedure that CHABA used for estimating the effects of long-burst duration and the incorrect assumption that the recovery from a given TTS was independent of the pattern of noise that produced it. The derivation of the CHABA contours assumed a recovery pattern during the noise-free intervals that was incorrect. Instead of being convergent as assumed, recovery curves following repeated exposures are essentially parallel (see Fig. 6). This pattern of interburst recovery dictates that the time which would be required for total recovery becomes longer as the daily exposure progresses.

Johnson *et al.* (1976b) were interested in the growth of TTS as a consequence of 24-h exposure to intermittent noise. Specifically, these investigators were interested in whether intermittent noises produce asymptotic threshold shifts; if it is asymptotic, whether the ATS be less for interrupted noises than for continuous noise of the same energy; whether the recovery patterns differ for interrupted and continuous noise exposures of equal energy.

The results clearly indicated an asymptote in the growth

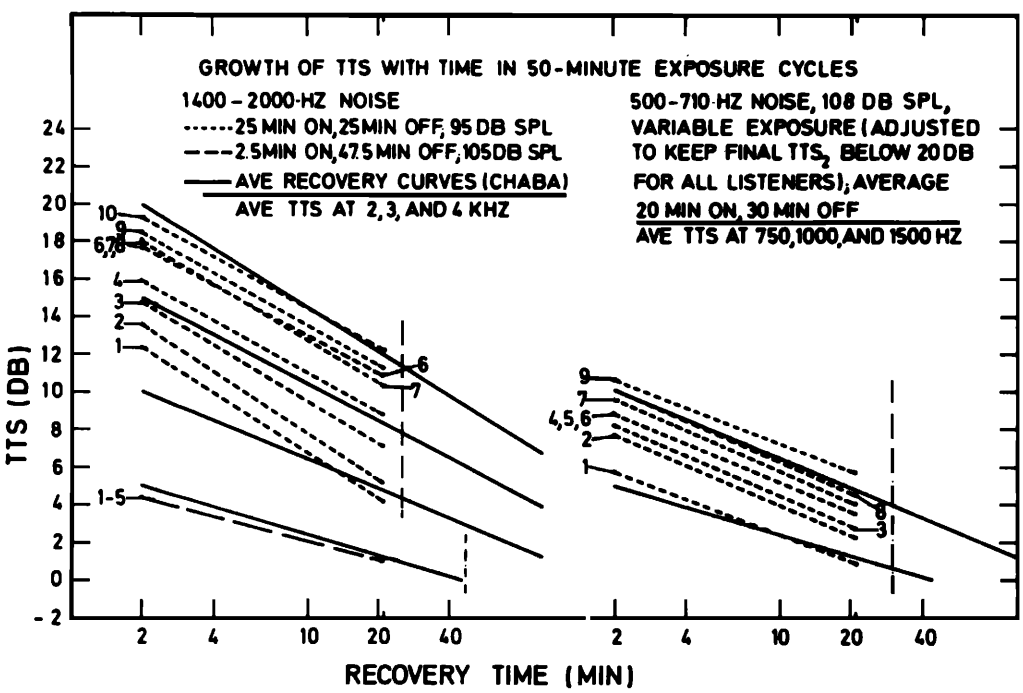

FIG. 6. Recovery from TTS during noise-free periods produced by repeated exposure to intermittent noise with a 50% duty cycle. The upper curves in the left panel indicate average recovery at 2.0, 3.0, and 4.0 kHz from exposure to ten successive 25-min exposures at 95 dB SPL, while the lower curves are from five successive 2.5-min exposures at 105 dB. The right panel shows average recovery at 0.75, 1.0, and 1.5 kHz from ten exposures to a 0.5 to 0.71-kHz noise band at 108 dB. Figure taken from Ward (1970).

of TTS for exposure to four different patterns of interrupted pink noise. Contrary to what might logically be expected, the asymptotic levels were reached earlier when the noises were interrupted than when the exposure was continuous. The ATSs measured for the interrupted noises were less than was produced by a continuous noise of the same energy. Even though, in some instances, the ATS was in the range of 5 dB, the recovery after the first hour post-exposure was virtually the same for all four interruption patterns and the continuous noise. Although the investigators take this last observation as supporting the equal-energy model for noise hazard, the small changes measured in threshold shift approach levels of measurement error making their interpretation tenuous.

Mills (1982) also was interested in the effects of noise interruption, particularly the variables of on-time and duty cycle on TTS for exposure durations of 24 to 32 h. TTS increased for the first 8 h and then remained relatively constant much like the TTS development for exposure to continuous noise. The fact that ATS is not a simple function of on-time or duty cycle is illustrated clearly in Fig. 7. For on-times of 10 to 10 000 s, duty cycle (Ward's on-fraction) was the determining factor. From the results using 75% and 90% duty cycles, one can observe that off-times of only a few seconds can reduce the ATS.

IV. TTS AS PREDICTOR OF NIPTS

Many of the investigations of TTS were motivated by attempts to establish these measures as a method for predicting individual susceptibility to NIPTS. These studies were predicated on the assumption that the variability demonstrated in the amount of PTS resulting from apparently similar noise histories was due to an inherent biological sensitivity to the noxious properties of acoustic stimulation. A corollary to this assumption was the notion that this predisposition was global and that this susceptibility would hold for the infinite variety of noise conditions. These assumptions represent a philosophical viewpoint that some people tend to be inferior in many traits than other people which Ward (1965) labeled as "inferior goods." Implicit in this approach is the belief that people who will develop more NIPTS would also show more TTS from a given noise exposure and would thereby be identified as susceptible. Carrying this simplistic notion even further was the expectation that the distribution of susceptibility would be distributed bimodally and people could be assigned to one of two categories, those of high risk for NIPTS and those at little or no risk.

Unfortunately, the data did not support these assumptions, and relation between TTS and PTS did not prove to be that simple. Ward (1973), in an excellent review of this subject, reported that correlations among threshold shifts resulting from stimulation by different ranges of frequency were small, in the range of 0.3. Correlations among measures of TTS from different test methods involving exposure to the same frequency range were about 0.55. Test–retest correlation of TTS measured at the frequency maximally affected with a 6-month intervening interval was 0.65. From a factor analysis of his data, Ward identified a common factor of general susceptibility to TTS but found that this factor would only account for a third of the commonality of his correlation matrix. These data would not support the concept of universal susceptibility of an individual to the effects of noise, nor would the data lead us to expect a quick simple test that would provide us with a method for identifying people who have an increased risk for NIPTS.

The inability to identify a simple predictor of NIPTS from measures of TTS seems to have had a damping effect on interest in TTS research on the part of sponsoring agencies and, perhaps as a consequence, in the interest in the scientific community. This is unfortunate. Because we haven't been able to find such a predictor thus far does not mean that one will never be developed, nor does it mean that research which focuses on the relation of noise properties to temporary threshold shift has no value. Studies of TTS still represent the only ethical method with sufficient control for developing information regarding the effects of noise on human hearing and for comparison with TTS and PTS data from laboratory animal models.

Recognition of the importance of the recovery pattern from TTS for identification of hazardous noise conditions has produced some doubt about the appropriateness of using TTS_2 to characterize temporary threshold shift. When recovery from TTS is prolonged, the degree of hazard of the producing exposures as indicated by measures of TTS_2 is not maintained throughout the recovery period. Ward (1970) postulates, that for exposure conditions likely to prolong recovery, i.e., high-intensity, high-frequency intermittent noise, TTS_{30} or TTS_{1000}, might be better indices. Kraak (1973, 1980) makes a case for using the time integral of TTS (ITTS) over the entire exposure and recovery period rather than a measure taken at one point in the time course of recovery as an index of hazard and susceptibility. Much of the evidence he uses to support use of ITTS as a predictor of susceptibility is indirect, i.e., ITTS correlated with noise dose and noise dose correlated with NIPTS. Kraak (1982) cites a 1976 dissertation by Richartz as the only direct, cor-

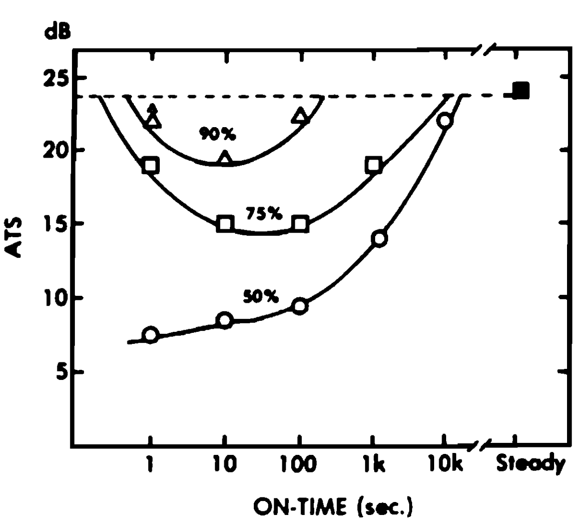

FIG. 7. Asymptotic threshold shifts (ATS) produced by 24-h exposures to a wide band of noise at L_A of 92.5 dB, with differing on-times. The parameter is the duty cycle. Figure is taken from Mills (1982).

relative study of ITTS and NIPTS. At 4 kHz, this correlation coefficient was 0.85. These results are promising. However, Kraak points out that the demonstrated relations of ITTS and PTS are valid for group data. He states further that for estimates of individual sensitivity TTS_2 or another measure of TTS at one point in the recovery process may be used. From Kraak's description of the method for measuring ITTS (1980), it seems too cumbersome to be practical for clinical and field applications but the method merits evaluation.

V. SUMMARY

Growth of TTS reaches an asymptote (ATS) following 8 to 10 h of exposure to noise, whether it is steady or intermittent. Both growth and recovery can be described by simple exponential functions. When the exposure is to octave bands of noise, the maximum shift occurs at frequencies about 1/2 oct above the center frequency of the band for much of the auditory range. The exception to this shift to higher frequencies is observed when the octave bands are in the frequency range 125 Hz and below. ATSs of 30 dB or less demonstrate a relatively systematic mathematic relationship to the octave band level of the noise. The relations apply for much of the human auditory frequency range and to data from not only humans but monkeys and chinchilla as well. Data from ATS studies tend to support the postulate relating NIPTS following 10 years of exposure to the TTS_2 measured after an 8-h exposure to the same noise. The remarkable individual variability observed with short exposure TTS and NIPTS also is observed in measures of ATS.

Levels of noise identified as effective quiet vary with the frequency content of the noise, ranging from 77 dB SPL for an octave band centered at 250 Hz to 65 dB for the band centered at 4000 Hz. These estimates are significantly less than was assumed in constructing the CHABA contours.

Studies of both effective quiet and asymptotic threshold shift provide estimates of noise levels that represent no risk to hearing. These estimates are amazingly similar from these two quite different investigative approaches. For broadband noise, the estimate from the effective-quiet approach is 76 dBA, while ATS studies indicate the the level to be 78 dBA.

The relationship of TTS to the properties of intermittent noise continues to be complex, depending on level, frequency, and duty cycle of the noise. The on-fraction rule that played a role in the development of the CHABA damage risk criteria has been shown to apply only to a limited number of intermittent conditions.

Recovery from TTS produced by high-level, high-frequency intermittent noise has been shown to be prolonged. TTS_2 may not be the appropriate index of risk in instances of prolonged recovery. Further, the convergent pattern of recovery assumed to occur between bursts of noise by CHABA has been shown to be unwarranted. Recovery from TTS is not independent of the conditions that produced the TTS.

A method to predict susceptibility to NIPTS using measures of TTS still has not been identified. The search for a reliable, valid procedure continues.

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