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Hearing loss from interrupted, intermittent, and time varying Gaussian noise exposures: The applicability of the equal energy hypothesis

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Eight groups of chinchillas ($N=74$) were exposed to various equivalent energy [100 or 106 dB(A) sound pressure level (SPL)] noise exposure paradigms. Six groups received an interrupted, intermittent, time varying (IITV) Gaussian noise exposure that lasted 8 h/d, 5 d/week for 3 weeks. The exposures modeled an idealized workweek. At each level, three different temporal patterns of Gaussian IITV noise were used. The 100 dB(A) IITV exposure had a dB range of 90–108 dB SPL while the range of the 106 dB(A) IITV exposure was 80–115 dB SPL. Two reference groups were exposed to a uniform 100 or 106 dB(A) SPL noise, 24 h/d for 5 days. Each reference group and the three corresponding IITV groups comprised a set of equivalent energy exposures. Evoked potentials were used to estimate hearing thresholds and surface preparation histology quantified sensory cell populations. All six groups exposed to the IITV noise showed threshold toughening effects of up to 40 dB. All IITV exposures produced hearing and sensory cell loss that was similar to their respective equivalent energy reference group. These results indicate that for Gaussian noise the equal energy hypothesis for noise-induced hearing loss is an acceptable unifying principle.

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I. INTRODUCTION

Understanding the relation between noise-induced hearing loss and the noise exposure variables for the purpose of hearing conservation practice becomes more complex when the exposure is interrupted, intermittent and time varying (IITV). This complexity could be reduced if the equal energy hypothesis (EEH) could be shown to be valid for IITV exposures. While there are exposure conditions where the EEH has been shown to be valid (Dolan *et al.*, 1976; Eldredge *et al.*, 1959; Atherley and Martin, 1971; Clark, 1991) there are also numerous examples where it does not hold (e.g., Fredelius *et al.*, 1987; Mills *et al.*, 1981; Clark *et al.*, 1987; Ward and Turner, 1982; Campo and Lataye, 1992; Ward, 1991; Lataye and Campo, 1996; Patuzzi, 1998; Pourbakht and Yamasoba, 2003). While most industrial noise exposures are typically of the IITV type there does not appear to be any hearing loss data from experimental exposures designed to replicate some of the essential features of an industrial noise environment. Ward (1991, p. 164) defined an IITV exposure as: “An exposure that involves long periods of effective quiet (several hours) will be defined as being *interrupted*, one with short break (a few seconds to an hour) will be characterized as *intermittent*, and one in which the level varies but remains above effective quiet is simply *time varying*.” Typically exposures that are interrupted and/or intermittent produce lower levels of hearing loss than do continuous exposures (Clark and Bohne, 1992; Patuzzi, 1998; Campo and Lataye,

1992; Fredelius and Wersall, 1992; Pourbakht and Yamasoba, 2003). This seems reasonable since during the quiet periods the ear has some time to recover from any threshold shift. The EEH predicts no reduction in hearing loss for interrupted exposures and thus its application to estimating the hazards of an IITV exposure to hearing would be conservative.

While considerable data exist on interrupted and intermittent exposure paradigms there is virtually no data on long-term, time varying exposures. One of the earliest studies of interrupted/intermittent exposures that produced a permanent threshold shift (PTS) can be traced back to the work of Miller *et al.* (1963) who showed that threshold shifts following daily exposures could decrease despite the recurring exposure. Since that time a number of experiments (Clark *et al.*, 1987; Subramaniam *et al.*, 1991; Boettcher, 1993; Hamernik *et al.*, 1994) have confirmed this phenomenon, which has been referred to as a toughening effect. While an interrupted exposure, that produces toughening, has often been shown to make the cochlea less susceptible to PTS from a subsequent traumatic exposure, other studies (Hamernik and Ahroon, 1998, 1999; Ahroon and Hamernik, 1999) including the results found in Miller *et al.* (1963), have shown that the cochlea, although toughened by an interrupted noise exposure, is not protected from the noise that produced the toughening when compared to an equivalent energy uninterrupted control group.

A phenomenon similar to the toughening effect was found by Canlon *et al.* (1988). They showed that exposure of subjects to low level noise prior to a more traumatic exposure could have the effect of reducing the PTS from the

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higher level exposure. The low level exposure was referred to as a conditioning or priming exposure and the reduction in PTS as the conditioning effect. Evidence is accumulating that both the conditioning and toughening effects are the result of the upregulation of enzymes involved in the control of reactive oxygen and nitrogen species known to increase following noise exposure (Bobbin *et al.*, 1995; Jacono *et al.*, 1998; Ohlemiller *et al.*, 1999) and to be toxic to sensory and supporting cells (Yamane *et al.*, 1995; Ohinataab *et al.*, 2000) in the cochlea.

For an individual, the acoustic environment both on and off the job is IITV in character and the biochemical processes underlying both the toughening and conditioning effects are likely to be continuously active. Thus, the IITV exposures of the industrial environment should elicit toughening effects while the lower level sounds of, for example, transportation, entertainment, etc., may elicit conditioning effects. Despite these inherent protective reactions to noise, hearing loss in the industrial population continues to increase.

The objective of the experiments reported here was to compare the effects on hearing of IITV exposures, modeled after an idealized three-week work schedule, with those of a uniform equivalent energy continuous exposure in order to establish the extent to which the EEH applies to Gaussian IITV exposures. A by-product of the interrupted and intermittent features of the experimental design was the ability to acquire data on the toughening phenomenon and the extent of its effect on noise-induced trauma.

II. METHODS

A. Auditory evoked potential

Seventy-four chinchillas were used as subjects. Each animal was anesthetized [IM injection of Ketamine (35 mg/kg) and Xylazine (1 mg/kg)] and made monaural by the surgical destruction of the left cochlea. During this procedure a bipolar electrode was implanted, under stereotaxic control, into the left inferior colliculus and the electrode plug cemented to the skull for the recording of auditory evoked potentials (Henderson *et al.*, 1973; Salvi *et al.*, 1982). The auditory evoked potential (AEP) was used to estimate pure tone thresholds. The animals were awake during testing and restrained in a yoke-like apparatus to maintain the animal's head in a constant position within the calibrated sound field. AEPs were collected to 20 ms tone bursts (5 ms rise/fall time) presented at a rate of 10/s. Each sampled wave form was analyzed for large-amplitude artifact, and, if present, the sample was rejected from the average and another sample taken. Averaged AEPs were obtained from 250 presentations of the 20 ms signal. Thresholds were measured using an intensity series with 5 dB steps at octave intervals from 0.5 to 16 kHz. Threshold was defined to be one-half step size (2.5 dB) below the lowest intensity that showed a "response" consistent with the responses seen at higher intensities. Additional details of the experimental methods may be found in Ahroon *et al.* (1993).

B. Experimental protocol

Following a two-week postsurgical recovery, three AEP preexposure audiograms were obtained (on different days) on each animal at octave intervals between 0.5 and 16.0 kHz. If the mean of the three audiograms fell beyond one standard deviation (s.d.) of laboratory norms (Hamernik and Qiu, 2000), in the direction of poorer thresholds at more than one test frequency, the animal was rejected. The animals were randomly assigned to one of eight experimental groups with 8–16 animals/group. Two groups were exposed to a uniform, continuous exposure for five days at 100 or 106 dB(A) sound pressure level (SPL). Each of these two groups constituted an equal energy reference group for the IITV exposures. Six groups received a 19-day IITV exposure as detailed below.

The animals were exposed four (or less) at a time to one of the noise conditions detailed below. During exposure, animals were given free access to food and water and were rotated through a bank of six cages daily. The SPLs, across cages, in the middle of each cage, varied within less than ± 1 dB. For the five-day uniform, continuous reference exposures, animals were removed daily for less than 0.5 h for AEP testing. The mean of the five audiograms thus obtained defined asymptotic threshold (AT). For the six IITV groups the animals were tested at the end of the daily exposure on days 1, 2, and 3 and 17, 18, and 19. The difference between the threshold measured following the first day (T_1) and the mean of the thresholds measured following the last three days (T_{17-19}) of the exposure was accepted as an estimate of threshold recovery or toughening (T_r) [i.e., $T_r = (T_1) - (T_{17-19})$]. Thirty days following the last exposure day for all exposure paradigms, three more audiograms were collected on different days and the mean used to define permanently shifted thresholds or permanent threshold shift (PTS).

C. Histology

Following the last AEP test protocol, each animal was euthanized under anesthesia and the right auditory bulla removed and opened to gain access to the cochlea for perfusion. Fixation solution consisting of 2.5% glutaraldehyde in veronal acetate buffer (final pH=7.3) was perfused through the cochlea. After 12–24 h of fixation the cochlea was post-fixed in 1% OsO₄ in veronal acetate buffer. Surface preparation mounts of the entire organ of Corti were prepared (Engstrom *et al.*, 1966) and inner hair cell (IHC) and outer hair cell (OHC) populations were plotted as a function of frequency and location using the frequency-place map of Eldredge *et al.* (1981). Missing cells were identified by the presence of a characteristic phalangeal scar. For purposes of this presentation, sensory cell population data are presented as group averages (in percent missing) taken over octave band lengths of the cochlea centered on the primary AEP test frequencies and as the group mean total number of IHCs or OHCs missing.

D. Noise measurement and analyses

During the exposures the noise field was monitored with a Larson Davis 814 sound level meter equipped with a

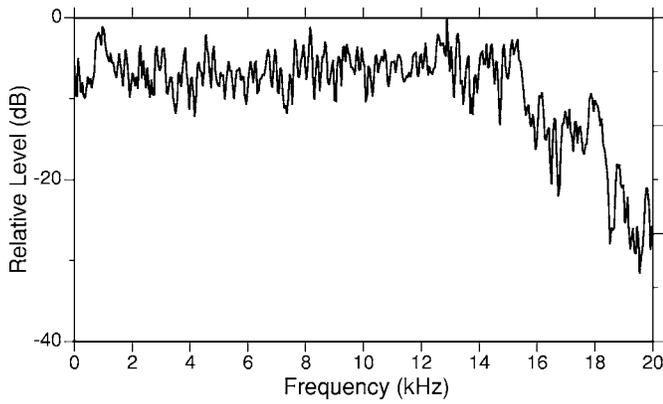


FIG. 1. The relative spectrum level of the unweighted 100 dB(A) SPL Gaussian noise. The 106 dB(A) SPL Gaussian noise had an unweighted spectrum that was qualitatively similar to the 100 dB(A) SPL noise.

1/2 in. microphone. The acoustic signal produced by the Electro-Voice Xi-1152/94 speaker system was transduced by a Brüel and Kjær 1/2 inch microphone (Model 4134), amplified by a Brüel and Kjær (Model 2610) measuring amplifier and fed to a Windows PC-based analysis system. The signal was sampled at 48 kHz with a recording duration of 5.5 min. The design and digital generation of the acoustic signal is detailed in Hsueh and Hamernik (1990, 1991).

E. Noise exposures

Each exposure had in common the same flat spectrum between 0.125 and approximately 15.0 kHz shown in Fig. 1. Experimental group numbers are concisely defined in Table I. The uniform uninterrupted exposures, groups G43 and G94, were presented at 100 and 106 dB(A) SPL, respectively, and served as reference groups for the IITV exposures. All exposures at a given level had approximately the same total energy. The two reference groups [G43:

100 dB(A) and G94: 106 dB(A)] were exposed for 24 h/d for 5 d. These exposures were interrupted once daily for less than a half hour for AEP testing. The six IITV exposures were structured to model an idealized three-week work shift. Each daily exposure consisted of two 4.25 h periods with a 1 h break in between. Each 4.25 h exposure was interrupted for 15 min and each five-day sequence was separated by a two-day break. The time varying SPL for each of the IITV exposures followed one of three different “roughly Gaussian” styled profiles. The SPL for IITV Groups G83, 84 and 85 varied from 90 to 108 dB; for Groups G86, 87 and 88 the SPL varied from 80 to 115 dB. Thus, each of the three IITV exposures at a given energy level differed only in their patterns of the time varying SPL. A schematic of the six IITV exposure paradigms and the group numbers assigned to each is shown in Fig. 2. It should be noted that there was no *a priori* reason for the choice of the Gaussian sound level patterns shown in Fig. 2. An example of the noise level recorded for one of the IITV exposures (G84) over one day is shown in Fig. 3. Animals were returned to the colony following the final hour of each daily exposure.

F. Statistical analysis

The permanent threshold shift (PTS) and sensory cell losses in octave-band lengths of the cochlea were compared among the groups of animals for each noise exposure level [100 and 106 dB(A) SPL] using a two-way, mixed model analysis of variance (ANOVA) with repeated measures on one factor (frequency). Analysis of PTS and sensory cell losses was performed using a completely within-subject analysis. The probability of a type 1 error was set at 0.05. Statistically significant main effects of frequency were expected and found in all of the following analyses because of the frequency-specific nature of the audibility curve of the

TABLE I. Experimental groups defined.

Group No.	Equivalent energy SPL dB(A)	SPL profile	Exposure conditions
G-43	100	—	uniform SPL, 24h/d for 5d
G-85	100		IITV, 90 to 108 dB over 19d
G-83	100		IITV, 90 to 108 dB over 19d
G-84	100		IITV, 90 to 108 dB over 19d
G-94	106	—	uniform SPL, 24h/d for 5d
G-88	106		IITV, 80 to 115 dB over 19d
G-86	106		IITV, 80 to 115 dB over 19d
G-87	106		IITV, 80 to 115 dB over 19d

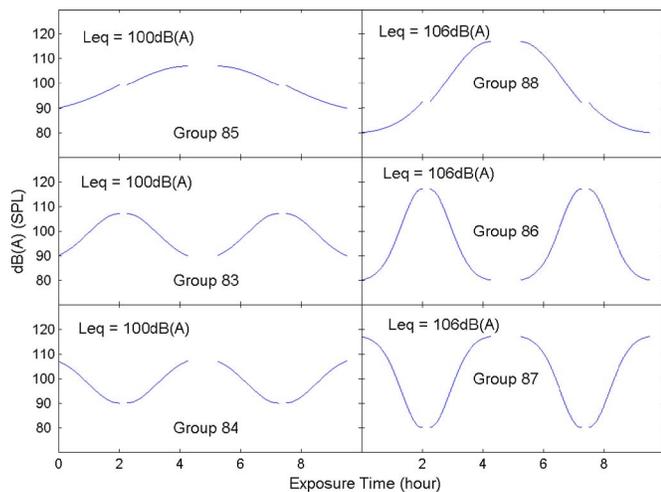


FIG. 2. A sketch of the SPL variations for the intermittent, interrupted and time varying noise exposure paradigm for the 100 and 106 dB(A) SPL groups. Each exposure sequence lasted for 19 days. Each daily exposure consisted of two 4.25 h periods with a 1 h break in between. Each 4.25 h exposure was interrupted for 15 min and each five-day sequence was separated by two-day break.

chinchilla and the noise exposure stimulus. For this reason main effects of frequency are not addressed in the presentation of the results.

III. RESULTS AND DISCUSSION

The group mean preexposure thresholds are shown as symbols in Fig. 4. The shaded area represents ± 1 s.d. of laboratory norms based on 1572 chinchillas. Only group G43 exhibited thresholds that were slightly lower (< 10 dB) than the other seven groups. Figures 5 and 6 show complete group mean data sets for the eight exposure conditions. The permanent threshold shifts (PTS) and the mean threshold recovery (T_r), i.e., toughening, developed during the IITV exposures are shown shaded in the upper panels of these figures. The lower panels show the IHC and OHC loss distribution in percent. Group mean total number of lost OHCs and IHCs along with standard errors of the mean (s.e.) are indicated. The bars on the data points in each figure represent one s.e. If a bar is not present the s.e. was less than the size of the symbol. The results for the two uniform and uninterrupted

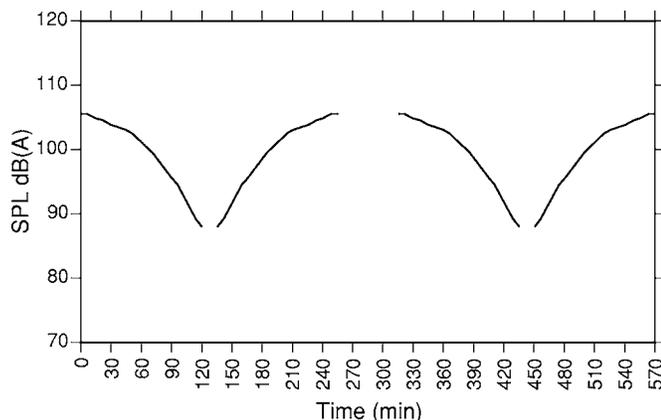


FIG. 3. An example of the actual SPL variations for the intermittent, interrupted and time varying noise exposure paradigm for group G84.

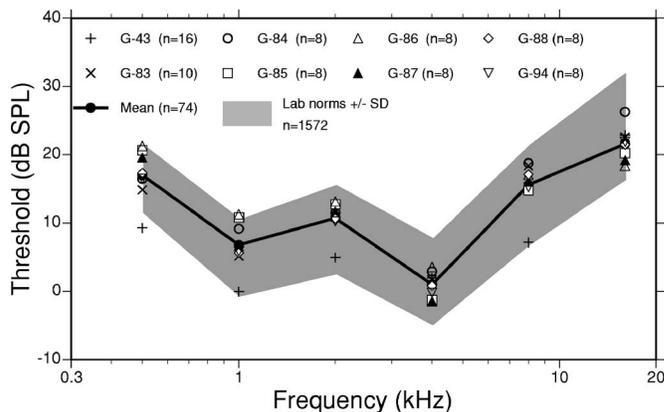


FIG. 4. Mean thresholds for the six experimental interrupted, intermittent and time varying exposure groups (G83, G84, G85, G86, G87, G88) and two uninterrupted reference groups (G43 and G 94) prior to noise exposure. The shaded area represents the mean preexposure thresholds ± 1 s.d. from the laboratory norm based on 1572 chinchillas. The bold line represents the mean preexposure thresholds of the 74 chinchillas included in this study.

reference exposures (G43 and G94) are shown in panel A of each figure. Visual inspection of these figures suggests the following. (1) All the IITV exposures produced a toughening effect that could approach 40 dB at some frequencies (see Fig. 6(G)). There was a noticeable frequency effect on T_r that was inversely related to the pattern of PTS. T_r was large at the lower frequencies where there was less PTS while T_r was small or zero at the highest frequencies where PTS was large. Although the IITV exposures showed a substantial toughening effect, this toughening did not result in a reduced PTS or an appreciable reduction in sensory cell loss when compared to the uninterrupted reference exposures. The issue of whether or not the toughened cochlea is protected from the noise that produced the toughening is not clear. Some exposure paradigms (Clark *et al.*, 1987) have yielded protection while others (Hamernik and Ahroon, 1998) have not. Since experimental paradigms differ considerably, comparisons across studies are difficult. (2) The frequency profile and magnitude of the PTS for the reference and IITV exposures, at both levels, are similar. (3) The distribution of IHC and OHC loss across equivalent energy groups is surprisingly similar.

The group mean PTS and cell loss for the four equivalent energy 100 dB (A) SPL exposures is compared in Fig. 7. The PTS across all four groups varied from about 5 dB at the lower frequencies to about 30 dB at the higher frequencies. The two-way ANOVA indicated that there was a statistically significant main effect of group ($F=6.1, df=3/222$) and no interaction between group and frequency ($F=0.92, df=15/222$). A one-way ANOVA as well as a posthoc analysis (Tukey test) revealed a statistically significant difference between two IITV groups (G83 and G84) and reference group G43 at the lower test frequencies of 0.5 and 1.0 kHz. These differences were less than 10 dB. All three IITV groups also showed significantly more PTS (10–15 dB) at 2.0 kHz compared to the reference group G43. Analysis of IHC loss across the four groups showed no main effect of group ($F=1.51, df=3/224$) and no interaction of group and frequency ($F=1.56, df=21/224$). The IHC loss was relatively small

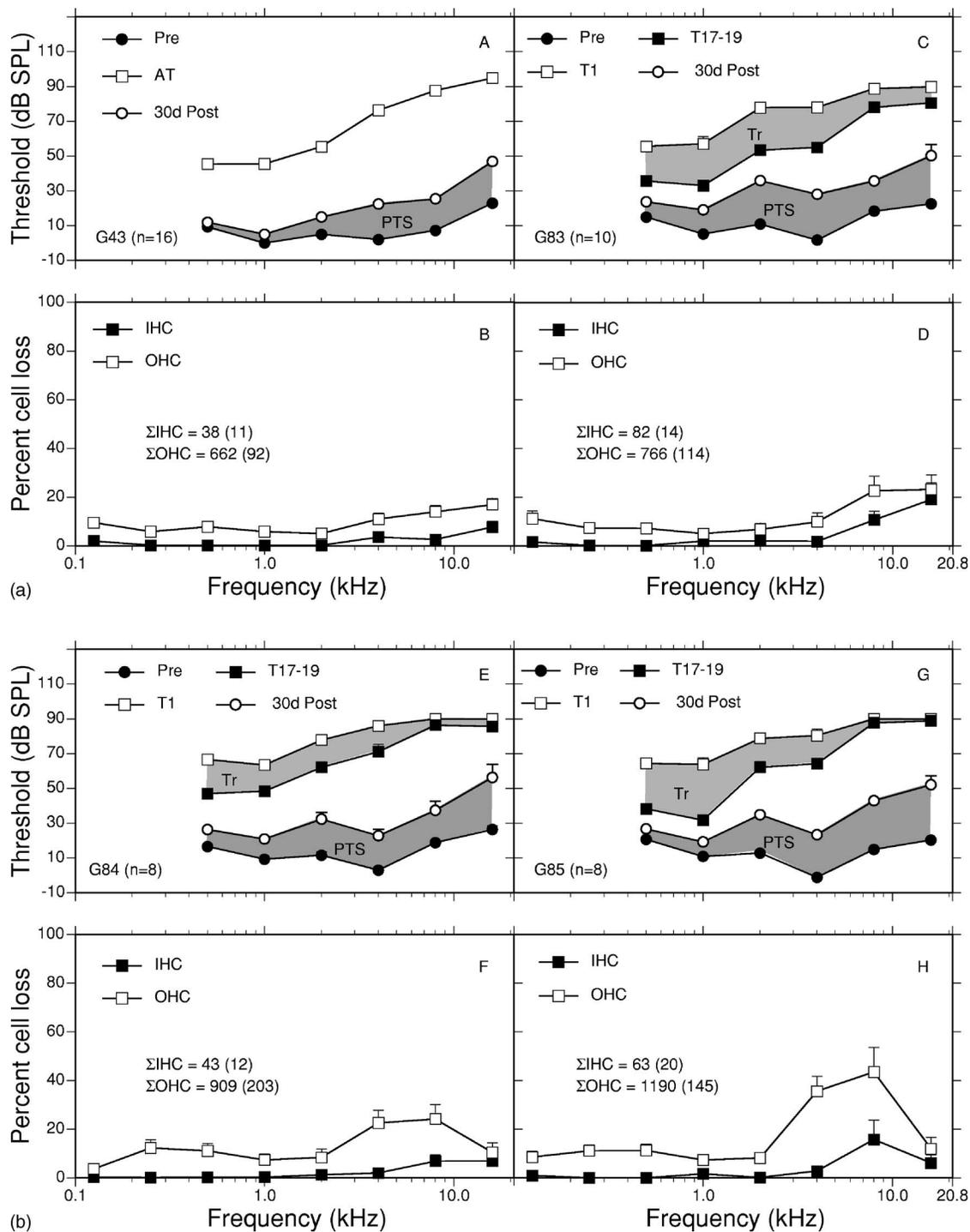


FIG. 5. Summary data from the four 100 dB(A) SPL exposures. Panel (A) shows the group mean asymptotic threshold (AT) and permanent postexposure thresholds. Panel (B) shows the group mean outer and inner sensory cell (IHC and OHC) losses (lower panel) for the uninterrupted reference group G43. Panels (C, D), (E, F), and (G, H) show a similar presentation of data for the three IITV equivalent energy exposures, G83, G84, and G85, respectively. Instead of AT, the group mean thresholds measured immediately following exposure on day 1 (T_1) and the group mean thresholds measured immediately following exposure on days 17, 18 and 19 (T_{17-19}) are shown. Toughening (T_r) and permanent threshold shifts (PTS) are shown shaded. The Σ indicates the group mean total number of OHCs or IHCs missing and () indicates the standard error.

and very near normal for frequencies up to about 4.0 kHz. At the higher frequencies (8 and 16 kHz) there were losses of 5% and 20% respectively. The OHCs showed a broad loss of 20–50% between 2.0 and 16 kHz. There was a significant main effect of group ($F=4.85, df=3/224$) and an interaction of group and frequency ($F=3.16, df=21/224$). At only 4 and 8 kHz was there a statistically significant greater amount of

OHC loss for the IITV group G85 relative to the reference group G43. For the three IITV exposures there was a significant difference only at 4 kHz where group G 85 showed about 22% more OHC loss than did group G83. Thus, among these four groups there were small differences in PTS at the low frequencies where there were no significant differences in OHC and IHC losses and while there were differences in

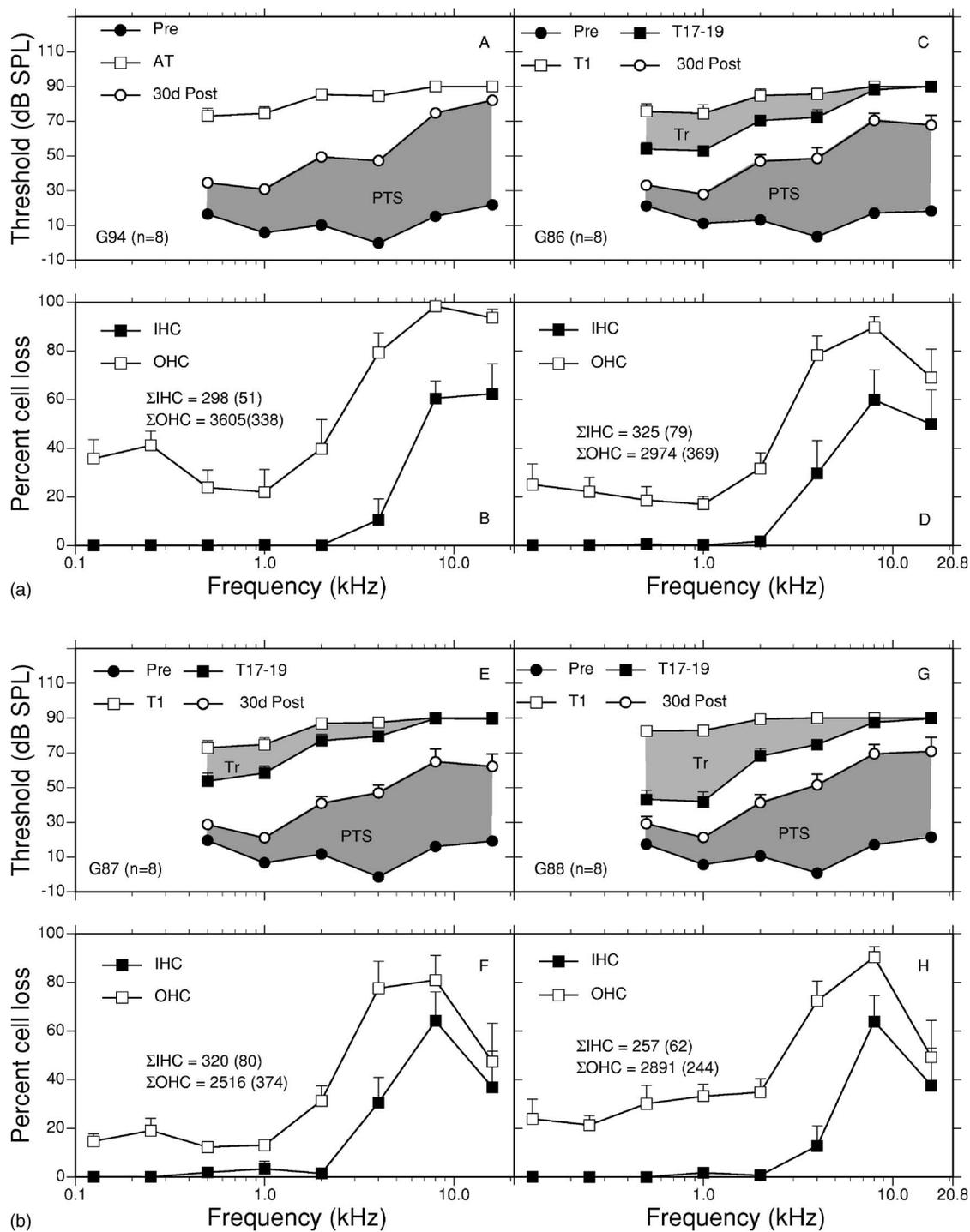


FIG. 6. Summary data from the four 106 dB(A) SPL exposures. Panels (A) shows the group mean asymptotic thresholds (AT) and permanent postexposure thresholds. Panel (B) shows the group mean outer and inner sensory cell (IHC, OHC) losses for the uninterrupted reference group G94. Panels (C, D), (E, F), and (G, H) show a similar presentation of data for the three IITV equivalent energy exposures, G86, G87, and G88, respectively. Instead of AT, the group mean thresholds measured immediately following exposure on day 1 (T_1) and the group mean thresholds measured immediately following exposure on days 17, 18 and 19 (T_{17-19}) are shown. Toughening (T_r) and permanent threshold shifts (PTS) are shown shaded. The Σ indicates the group mean total number of OHCs or IHCs missing and () indicates the standard error.

OHC loss at 4 and 8 kHz there was no significant difference in PTS. Based on the above it is clear that the toughened cochlea showed no protective effects. This result is consistent with our previous report (Hamernik and Ahroon, 1998) that showed no protective effect from a 10 to 30 dB T_r produced by long-term, high-level, narrow band impact noise

exposures in the chinchilla. These data further suggest that the EEH is a reasonable approach to the evaluation of Gaussian IITV long duration noise exposures.

The results of the four equivalent energy 106 dB(A) SPL set of exposures are summarized in Fig. 8. The two-way ANOVA showed that for PTS there was a main effect of

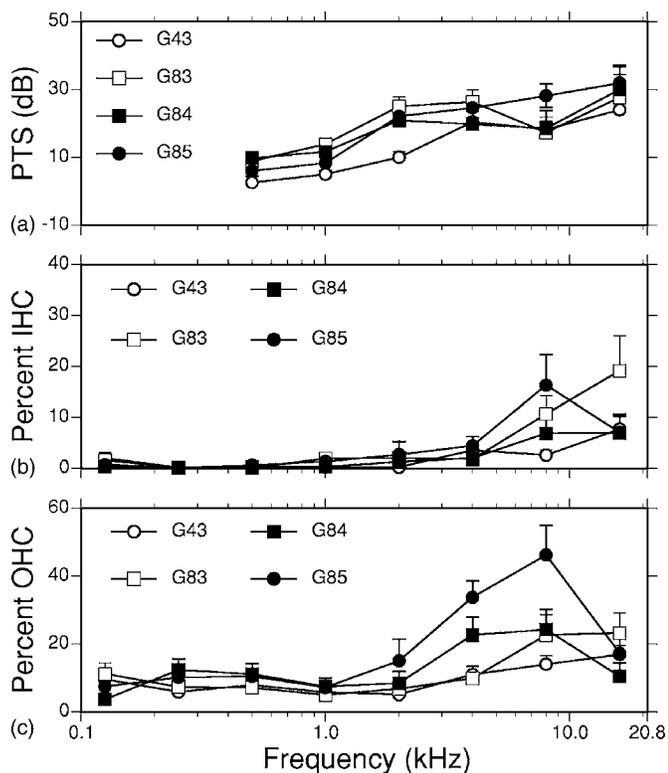


FIG. 7. A comparison of the PTS and cell loss data for the four 100 dB(A) SPL exposures. (a) The permanent threshold shifts (PTS). (b) The percent inner hair cell (IHC) loss. (c) The percent outer hair cell (OHC) loss.

group ($F=4.35, df=3/168$) and no interaction of group and frequency ($F=0.35, df=15/168$). The one-way ANOVA and Tukey tests indicated significantly less PTS (~ 10 dB) at only one frequency (1.0 kHz) for each IITV group (G86, G87 and G88) relative to the uninterrupted reference group (G94). There was no significant main effect of group ($F=0.28, df=3/224$) and no interaction of group and frequency ($F=0.68, df=21/224$) for IHC loss. The IHC population was very near normal between 0.125 and 2.0 kHz but showed losses of 30–60% from 4.0 to 16 kHz. There was a broadly distributed loss of OHCs across the entire cochlea in all four 106 dB(A) SPL groups with severe losses above 2.0 kHz. There was a significant main effect of group ($F=6.58, df=3/224$) and no interaction of group and frequency ($F=1.07, df=21/224$). There were no statistically significant differences in OHC loss among the three IITV groups and between each IITV and the reference group G94 with the exception of the mean percent OHC loss at 0.250 and 16 kHz where the uninterrupted reference group G94 showed more OHC loss compared to the three IITV groups. The similar amount of PTS and sensory cell loss across most of the test frequencies for the IITV and reference groups indicates that the toughening effects did not provide protection from the 106 dB(A) SPL IITV noise exposures. At this higher level, where the hearing and sensory cell loss is substantial, the EEH appears to be an acceptable unifying principle. This is consistent with the results of the 100 dB(A) exposure.

The results for both the 100 and 106 dB(A) SPL IITV exposures contrast with several experiments which have

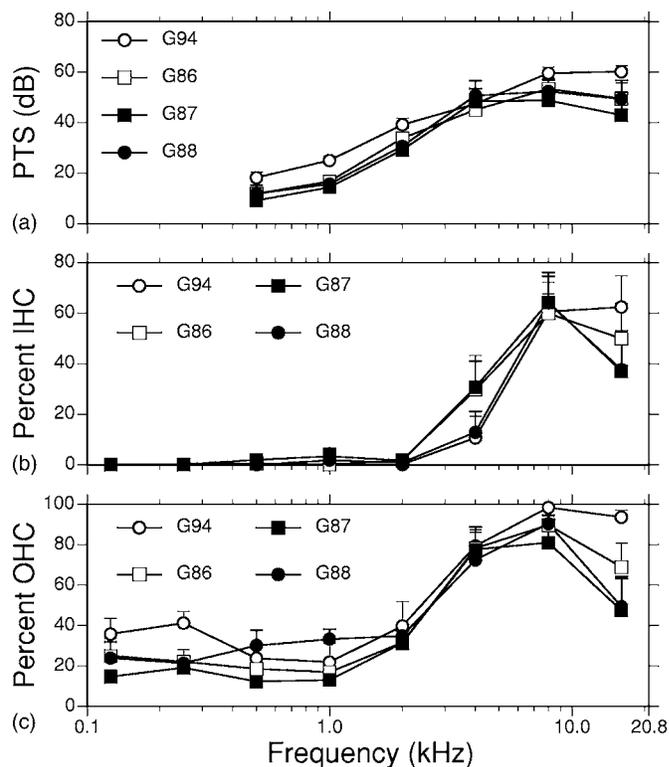


FIG. 8. A comparison of the PTS and cell loss data for the four 106 dB(A) SPL exposures. (a) The permanent threshold shifts (PTS). (b) The percent inner hair cell (IHC) loss. (c) The percent outer hair cell (OHC) loss.

demonstrated that intermittent noise exposures produce significantly smaller PTS and sensory cell loss than energy equivalent continuous noise (Patuzzi, 1998; Campo and Lataye, 1992; Fredelius and Wersall, 1992; Pourbakht and Yamasoba, 2003). These referenced studies were, however, of much shorter duration than the three-week IITV exposure in this study and used very different noise (pure tones, band limited noise) that was presented at a constant SPL. In a study involving 135 chinchillas exposed to high level impact noise on an interrupted and uninterrupted schedule Hamernik and Ahroon (1998) showed that there was no correlation between the amount of toughening and the extent of PTS produced by the toughening noise. They concluded that a toughened cochlea is not protected from the noise that produced the toughening. In the present paper, while a few statistically significant effects for both PTS and OHC loss were observed between the IITV and the uninterrupted Gaussian exposure groups, the relatively small magnitude and inconsistent appearance of these differences support the application of the EEH to Gaussian IITV long duration exposures.

IV. CONCLUSION

Despite a toughening effect found for the IITV exposures, the findings from the present study indicate that steady, uninterrupted Gaussian exposures at 100 or 106 dB(A) SPL produce similar effects on hearing as Gaussian IITV exposures of equivalent energy. Under the conditions of exposure reported here, the EEH, that forms the basis of current damage-risk criteria for noise exposure, appears to be insensitive to the IITV features of a Gaussian

noise exposure that follows an “on time” schedule of an ideal workweek. Thus this study, comparing the effects of continuous uniform exposures with IITV exposures of equivalent energy, suggests that the EEH can be used as a principal for estimating hearing loss from Gaussian IITV exposures. However, industrial noise environments are often non-Gaussian in character and there is evidence (Hamernik *et al.*, 2003) that variables other than energy affect the development of hearing loss from non-Gaussian exposures.

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