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Susceptibility of the noise-toughened auditory system to noise-induced trauma

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Abstract

The auditory system 'toughened' by an interrupted noise exposure has been shown in several reports, to be less affected by (or protected from) a subsequent high level noise exposure. A group of chinchillas ($n = 12$) was exposed to an interrupted noise at 95 dB SPL, 0.5 kHz octave band, 6 h/day for 10 days. Threshold shifts measured over the 10 day exposure showed that the animals responded by either (1) developing a large toughening effect (i.e., thresholds after day 10 of the exposure were considerably better than at the end of day 1) ($n = 5$) or (2) not showing any toughening, instead thresholds continued to get worse over the course of the exposure ($n = 7$). After a 5 day interval, during which thresholds of all the animals returned to normal, they, along with a control group ($n = 10$) not exposed to the interrupted noise, were exposed to an asymptotic threshold shift producing traumatic noise (127 dB peak SPL narrow band impact, 1 kHz center frequency, 24 h/day for 5 days). Auditory evoked potential audiometry and surface preparation histology showed that there were no statistically significant differences in the response of any of the above groups to the traumatic noise. The interrupted noise exposure, whether it produced a toughening or not, did not provide any protection from a subsequent high-level noise.

Key words: Noise trauma; Noise-induced toughening

1. Introduction

Several reports in the literature suggest that the response of the cochlea to a high level noise can be modulated by a previous lower level and innocuous exposure (e.g., Canlon et al., 1988; Campo et al., 1991; Subramaniam et al., 1993a). This paper focuses on one class of these experiments: the modulation produced by low level interrupted noise exposures that produce a toughening effect prior to exposure to a more severe noise. Toughening here refers to the amount by which a threshold shift (TS), produced by the first exposure of a repeating cycle of daily (interrupted) exposures, decreases with successive daily exposures, i.e., toughening, TS_R, is the difference between the TS measured after the first day exposure and that measured following the last day of the interrupted sequence of exposures [$TS_R = TS_1 - TS_x$]. Thus, with the interrupted paradigm, as long as the toughening exposure produces a TS, the amount of toughening can be quantified at each audiometric test frequency. This is a class of experiments that was first reported on by Miller et al. (1963) and followed up almost 25 years later by Clark et al. (1987). With results demonstrating a toughening effect on the cochlea it was natural to then expect that a toughened cochlea might be resistant to a subsequent and more severe exposure. While the Miller et al. results failed to demonstrate such a protective effect, protective effects have indeed often been found since then (e.g., Campo et al., 1991), although there have been some exceptions (e.g., White et al., 1998).

In the chinchilla, Henselman et al. (1994), using a 0.5 kHz octave band noise (OBN) presented at 95 dB SPL, 6 h/day for 10 days to toughen the chinchilla cochlea showed a large reduction in permanent threshold shift (PTS) and sensory cell loss following an acute exposure to 150 dB peak SPL impulses. McFadden et al. (1997) and Campo et al. (1991) used the same toughening

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paradigm as Henselman et al. and after a 5 day rest period, presented the subjects (chinchillas) with the 0.5 kHz OBN but presented at 106 dB SPL for 48 h. This exposure produced permanent changes in hearing thresholds and sensory cell loss. The toughened animals showed less PTS than the untoughened animals but sensory cell losses, which were limited to the outer hair cells (OHC), did not differ between the toughened and untoughened groups. Subramaniam et al. (1993a), using the same toughening and traumatic noise exposures as above, varied the presentation schedule of the toughening noise in each of three groups. They found very similar results: statistically less PTS in the toughened groups but no difference in the degree of OHC loss.

Using the same 95 dB SPL, 0.5 kHz OBN presented 6 h/day for 10 days to toughen the auditory system, Subramaniam et al. (1993b) presented the toughened animals with a 4 kHz OBN at 100 dB for 48 h. Despite a clearly toughened cochlea the animals had greater PTS and OHC loss than the untoughened animals. In a related piece of work, Subramaniam et al. (1992) toughened the animals with a 4 kHz OBN at 85 dB SPL, 6 h/day for 10 days and then used the 4 kHz OBN at 100 dB for 48 h to produce trauma. Two toughened groups were exposed to the higher level noise: one with a 5 day interval between toughening and trauma and one with only an 18 h interval between toughening and trauma. They found that the group that had the 5 day interval between toughening and trauma showed greater PTS but the same sensory cell loss as the untoughened animals while the group with the 18 h interval developed less PTS and sensory cell loss than the untoughened animals.

The above review has focused primarily on interrupted noise toughening paradigms that used a 0.5 kHz OBN as a stimulus. Other toughening paradigms have been shown to produce a TS_R across a broad range of audiometric test frequencies (e.g. White et al., 1998; Ahroon and Hamernik, 1999) without yielding a subsequent protective effect. The results of Hamernik and Ahroon (1999) are also relevant to the issue of protection. They showed, on the basis of a large population study of interrupted noise-induced toughening, that the toughened cochlea is not protected from the very noise that produced the toughening.

The brief review of the literature presented above suggests that there is not a clear consensus on the conditions under which the cochlea, preexposed to interrupted noise that produces toughening, is protected from a subsequent and more severe noise exposure. Our intention in this paper was to use an experimental paradigm somewhat similar to that of Henselman et al. (1994) in an effort to produce a consistent and robust protective effect.

2. Methods

Monaural chinchillas (1–2 years of age) were used as the experimental animal. Brainstem (inferior colliculus) auditory evoked potentials (AEPs) were used to estimate pure tone thresholds and surface preparation histology was used to quantify sensory cell populations. Details of the experimental methods, beyond those that are presented below, can be found in Ahroon et al. (1993).

2.1. Noise exposures

The toughening exposure consisted of a 0.5 kHz center frequency (CF) OBN presented at 95 dB SPL, 6 h/day for 10 days. The noise was generated by passing the output of a General Radio 1382 Random Noise Generator through a Brüel and Kjær Model 125 Graphic Spectrum Equalizer. The output of the filter was directed to an AB International Precedent Series 900 Amplifier and finally to a ElectroVoice TL550D low frequency speaker. The output of the speaker was calibrated and measured by a Brüel and Kjær Type 4134 half-inch condenser microphone and Brüel and Kjær Type 2610 Measuring Amplifier, calibrated by a Brüel and Kjær Type 4220 Pistonphone. The analog output of the measuring amplifier was fed to an Apple Macintosh Quadra 840AV computer system with 16-bit National Instruments NB-2100 audio board and sampled at 48 000 samples per second. A Wavetek Model 852 Dual HI/LO Filter provided anti-aliasing. A set of virtual instruments using the National Instruments LabVIEW™ graphical programming language performed the spectral and intensity analysis. The spectrum of the 0.5 kHz OBN stimulus is presented in Fig. 1a.

The traumatic noise exposure consisted of narrow band impacts (NBI) 400 Hz wide, having a 1.0 kHz CF, presented at the rate of 1 impact/s at 127 dB peak SPL for 24 h/day for 5 days. The traumatizing exposure produces an asymptotic threshold shift (ATS) condition (Carder and Miller, 1972). The impact noise stimulus was generated digitally using a LabView™ virtual instrument in which a fixed-length pulse was fed through a 4th-order, band-pass, Butterworth filter. The resulting waveform was played through the computer's (Macintosh Quadra 840 AV) sound output and fed to an AB International Precedent Series 900A amplifier. The output of the amplifier was fed to a JBL Model 2445J speaker with Model 2360H horn and Model 2360T transition piece. Fig. 1b shows the relative spectrum and temporal waveform of the 127 dB peak SPL narrow-band impact.

During exposure, individual chinchillas were confined to cages (10″×11″×16″) with free access to food and

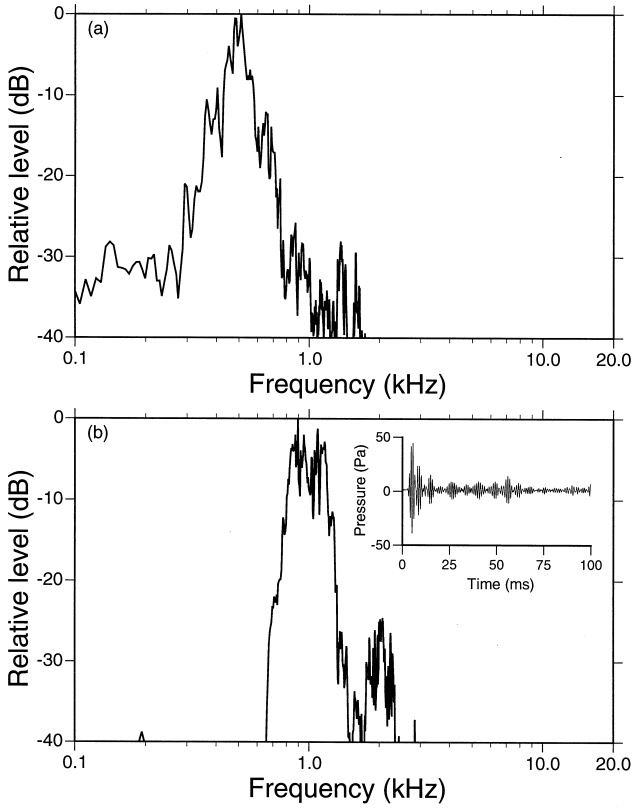

Fig. 1. a: The spectrum of the 0.5 kHz, 95 dB SPL octave band of noise used to toughen the auditory system. b: The spectrum and pressure-time history of the 127 dB peak SPL, narrow band impact that was used to produce hearing and sensory cell loss.

water. A maximum of six animals were exposed at a time. Peak and RMS SPLs in the exposure field were uniform to within 2 dB.

The experimental group of chinchillas ($n = 12$) was exposed to the 0.5 kHz OBN at 95 dB SPL for 6 h/day for 10 days. After a 5 day recovery period, the animals were exposed to the 1.0 kHz CF NBI presented at 127 dB peak SPL. A control group of 10 animals was exposed to only the high level NBI.

2.2. Threshold testing

Thresholds for all AEP audiograms were measured at octave intervals from 0.5 to 16.0 kHz. The mean (in dB SPL) of three threshold determinations measured on different days defined each animal's preexposure audiogram. For the 10 day interrupted exposure paradigm, a complete audiogram was measured immediately following the first and last two daily 6 h exposures in order to establish the magnitude and time course of the toughening phenomenon. The amount of toughening (TS_R) at each audiometric test frequency was defined as the difference between the threshold measured at a given frequency following the first day exposure and the mean of the thresholds (in dB SPL) measured following exposure on days 9 and 10. The animals were then allowed to recover to within 5 dB of the preexposure thresholds before being exposed to the high level impacts. This recovery period took 2–5 days. A complete audiogram was measured once daily during each of the 5 exposure days of the 127 dB peak SPL uninterrupted exposure and the average (in dB SPL) taken over the 5 days established the mean asymptotic threshold levels. Thirty days following the complete exposure protocol for each group, AEP audiograms were measured again on three different days and averaged for each animal to establish permanent postexposure threshold levels.

2.3. Histology

Following the last AEP test protocol, each animal was killed 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 postfixed in 1% OsO_4 in Veronal acetate buffer. Surface preparation mounts of the entire organ of Corti were prepared and inner and outer hair cell (IHC, OHC) populations were plotted as a function of frequency and location using the frequency-place map of Eldredge et al. (1981). For purposes of this presentation, sensory cell population data is presented as group averages taken over octave band lengths of the cochlea centered on the primary AEP test frequencies (Hamernik et al., 1989).

2.4. Statistical analysis

The dependent variables reported in this paper are (1) AEP thresholds, before, during, and following noise exposure(s), and (2) sensory cell losses in octave band lengths of the cochlea. Comparisons of groups of animals receiving different treatments were accomplished by mixed model analyses of variance with repeated measures on one factor (frequency). Analyses of thresholds within groups of animals, where necessary, were performed using completely within-subjects analyses of variance. The probability of a type I error was set at 0.05 for all analyses. Analysis of variance summary tables may be obtained from the authors.

2.5. Animal care

The care and use of the animals used in this study were approved by the SUNY Plattsburgh Institutional Animal Care and Use Committee. In conducting the research described in this report, the investigators ad-

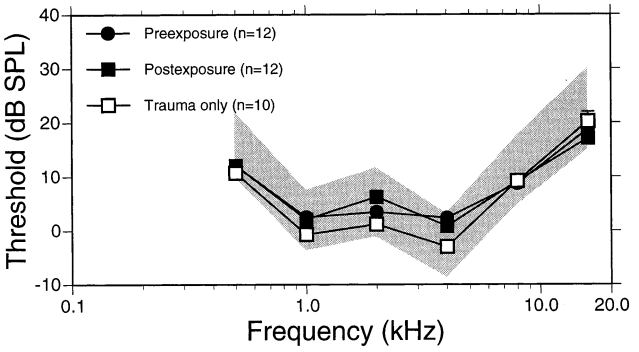

Fig. 2. Group mean AEP thresholds measured before (●) and 2–5 days after (■) the 0.5 kHz, 95 dB SPL toughening exposure in the experimental group. Also shown are the preexposure thresholds (□) for the untoughened control group. The shaded area represents one standard deviation above and below the laboratory norm for the chinchilla AEP audiogram ($n = 924$).

hered to the Guide for Care and Use of Laboratory Animals, as promulgated by the Committee on Care and Use of Laboratory Animals of the Institute of Laboratory Resources Commission on Life Sciences, National Academy of Sciences-National Research Council, revised 1985.

3. Results

In some of the following figures the shaded region on the AEP audiograms represents the mean normative AEP audiogram (±1 S.D.) based on a population of 924 chinchillas. The bars on the data points in each figure represent 1 S.E.M.; where no bar is shown the standard error was less than the size of the datum symbol.

In an experimental paradigm that entails a sequence of several exposures there is always a question of the status of the auditory system following any one of the exposures. In the case of conditioning with an 'innocuous' noise or toughening with the higher SPL exposures, the system has clearly been altered. Thus, for reasons that go back to the Davis et al. (1950) idea of the 'damaged ear theory' and some of the subsequent experiments that it generated (e.g., Mills, 1973, 1992; see also the review by Humes, 1984) the presentation of results is given in terms of shifted thresholds (dB SPL) rather than the more conventional threshold shifts.

Fig. 2 shows the group mean preexposure AEP audiograms for the experimental and control groups. Also shown is the AEP audiogram for the experimental group immediately prior to being exposed to the traumatic noise. All of these thresholds were within ±1 S.D. of laboratory norms. There is no statistically significant main effect of group for any of the three analyses but a significant interaction between group and frequency indicating that the AEP audiograms shown in Fig. 2 differed depending on frequency. This effect, it should be noted, amounts to a maximum of 5 dB at the 2 or 4 kHz test frequency depending on which group comparison is made. Thus thresholds of the experimental group measured prior to the toughening exposure and those measured 2–5 days after the toughening exposure were essentially the same. Except for the interaction effect (5 dB) at 4 kHz, the experimental and control groups also had similar thresholds prior to the traumatic exposure. The 10 day toughening exposure produced at most a 2 dB change in AEP thresholds at 2 kHz which is well within the approximately ±5 dB test-retest reliability of AEP audiometry. The main ef-

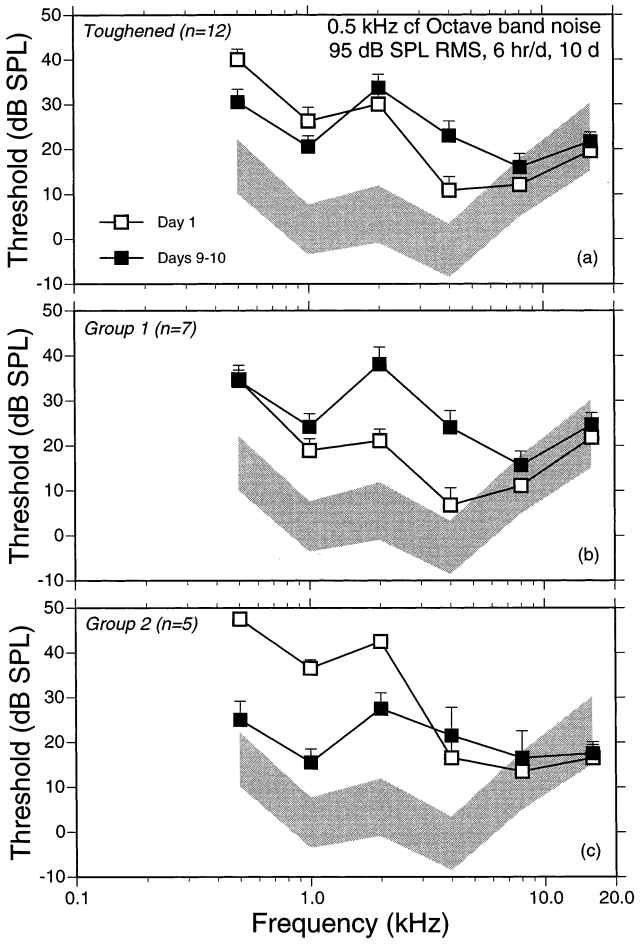

Fig. 3. a: The mean AEP thresholds for the entire group of animals exposed to the toughening noise paradigm measured after the first 6 h exposure (□) to the interrupted toughening noise and the mean of the thresholds measured after the day 9 and 10 (■) exposures. The vertical distance between the □ and ■ symbols is a measure of the amount of toughening ($TS_R = TS_1 - TS_{9,10}$) produced by the interrupted noise exposure. b and c: A similar presentation of threshold data but the toughened group has been broken down into subgroups 1 and 2 respectively. Group 1 represents those animals whose thresholds did not exhibit any $+TS_R$, while group 2 animals developed a robust TS_R.

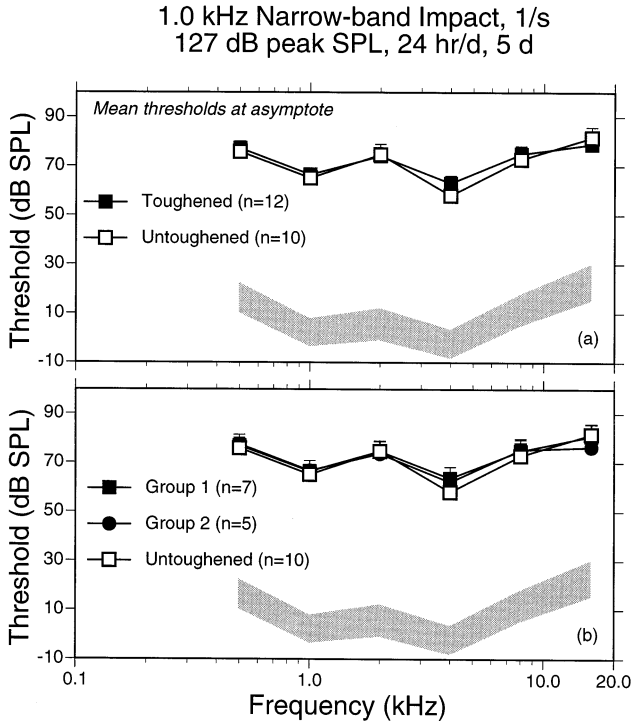

Fig. 4. a: The mean AEP asymptotic thresholds, measured over the course of the uninterrupted 5 day exposure to the 127 dB peak SPL impact noise, for the entire group of toughened (■) and untoughened (□) animals. b: A similar presentation of asymptotic threshold data but the toughened group has been broken down into subgroups 1 and 2. Group 1 (■) represents those animals whose thresholds did not exhibit any $+TS_R$, while group 2 animals (●) developed a robust TS_R.

fect of frequency was statistically significant but this is expected based on our knowledge of the chinchilla audiogram (Fay, 1988). Statistically significant main effects of frequency are expected in most of the following analyses because of the frequency specific nature of not only the audiogram but also the noise stimuli. For this reason main effects of frequency will not be repeatedly discussed.

The group mean AEP thresholds for the experimental group measured after the first 6 h exposure and the mean of the thresholds measured after the 9th and 10th day exposure are shown in Fig. 3a. The amount of toughening, TS_R, can be estimated by measuring the distance between the corresponding pairs of data symbols at each frequency. There is no statistically significant main effect of day of measurement but there is an interaction between day and frequency. The significant interaction reflects the approximately 10 dB positive TS_R at 0.5 kHz and the negative 12 dB TS_R at 4 kHz.

In the course of analyzing the data presented in this figure it became clear that the animals exposed to the toughening noise fell into two groups. One group, referred to as group 1 ($n=7$), showed a relatively small TS after the first 6 h exposure at several test frequencies; the TS grew with successive exposures so that by the 10th day, TS was greater than that measured after day 1 thus yielding a negative value of TS_R. The second subset (group 2, $n=5$) of the experimental group showed a consistent toughening effect. The group mean TS measured after the first and last two days of the toughening exposure for these two subgroups of the original experimental group is shown in Fig. 3b,c.

An analysis of the two sets of AEP audiograms shown in Fig. 3b indicates that there is a statistically significant main effect and a frequency interaction. The animals in group 1 had TSs at the end of the exposure that were significantly higher than those following day 1, i.e., a systematically negative value of TS_R. The group 2 animals also showed a statistically significant main effect and a frequency interaction. This reflects the 15–22 dB $+TS_R$ seen in Fig. 3c between 0.5 and 2.0 kHz. This dichotomy in the TS response to the toughening noise exposure in the experimental animals provided an opportunity to examine whether there was also a difference in the susceptibility to noise trauma between these two groups.

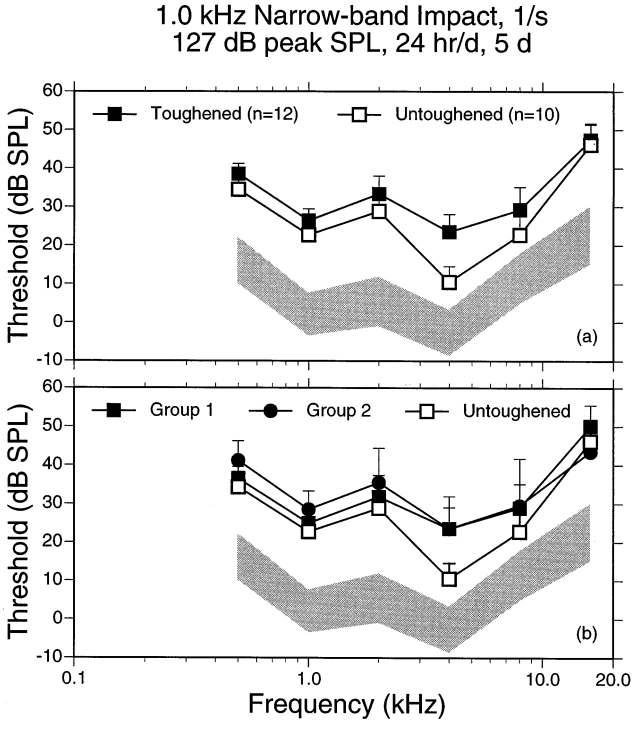

Fig. 5. a: The mean AEP thresholds, measured 30 days after the 127 dB peak SPL uninterrupted traumatizing exposure, for the entire group of toughened (■) and untoughened (□) animals. b: A similar presentation of 30 day post exposure threshold data but the toughened group has been broken down into subgroups 1 and 2. Group 1 (■) represents those animals whose thresholds did not exhibit any $+TS_R$, while group 2 animals (●) developed a robust $+TS_R$.

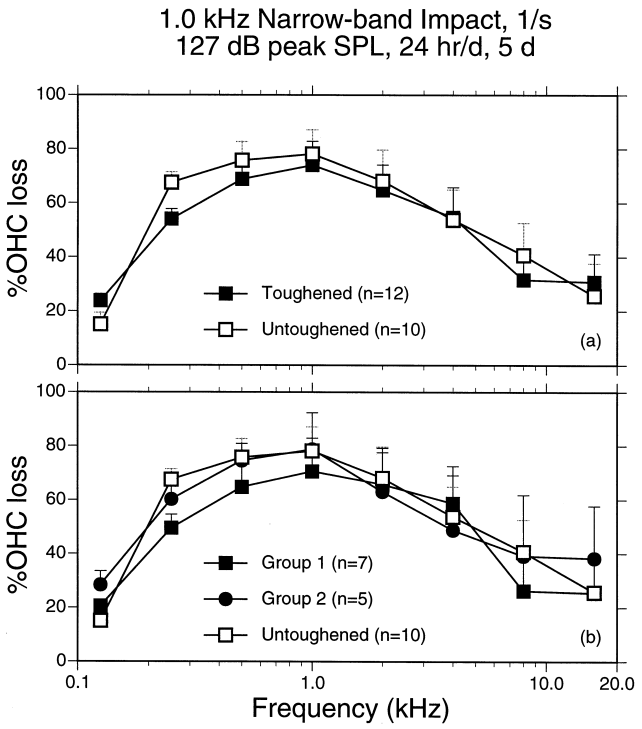

Fig. 6. a: The mean OHC loss over adjacent octave band lengths of the basilar membrane, measured 30 days after the 127 dB peak SPL uninterrupted traumatizing exposure, for the entire group of toughened (■) and untoughened (□) animals. b: A similar presentation of 30 day post exposure OHC loss data but the toughened group has been broken down into subgroups 1 and 2. Group 1 (■) represents those animals whose thresholds did not exhibit a $+TS_R$, while group 2 animals (●) developed a robust TS_R.

Fig. 4a shows a comparison between the thresholds measured at asymptote during the 127 dB peak SPL traumatic noise exposure for the complete experimental group and for the untoughened control group. For each group, the thresholds shown are the mean of the thresholds measured daily during the 5 day, 127 dB uninterrupted exposure. There is no statistically significant difference in the asymptotic response of the two groups. Fig. 4b shows a similar data presentation but with the experimental group separated into the group 1 and 2 classification defined above. There is no statistically significant difference in thresholds at asymptote among the two experimental groups shown in Fig. 4b.

The permanent effects of the traumatic exposure are shown in Figs. 5, 6 and 7. Fig. 5a shows the thresholds measured 30 days following the traumatic exposure in the toughened (experimental) and untoughened (control) groups. Although the thresholds of the toughened group are slightly elevated with respect to the untoughened group, there is no statistically significant effect of group nor is there an interaction between group and frequency. Fig. 5b shows a similar presentation of the permanent AEP changes in threshold but with the experimental group broken down into the group 1 and 2 classification. Again there is no statistically significant difference (neither a main effect of group nor an interaction of group and frequency) among these thresholds.

The percent OHC loss in the toughened and untoughened animals is shown in Fig. 6. There are no statistically significant differences between the groups taken as a whole (Fig. 6a) or between the toughened groups divided into the group 1 and 2 subgroups (Fig. 6b) despite the large TS_R in group 2. Fig. 7 shows a similar presentation of percent IHC loss. Striking is the large variability seen in the percent IHC losses across the groups. Although the mean percent IHC losses in the toughened group ($n = 12$) are smaller than for the untoughened group, these differences are not statistically significant. A similar conclusion applies to the percent IHC losses shown in Fig. 7b where the toughened group is divided into the two subgroups. Despite a large TS_R in group 2 there was no difference in the percent IHC losses among the groups shown in this figure.

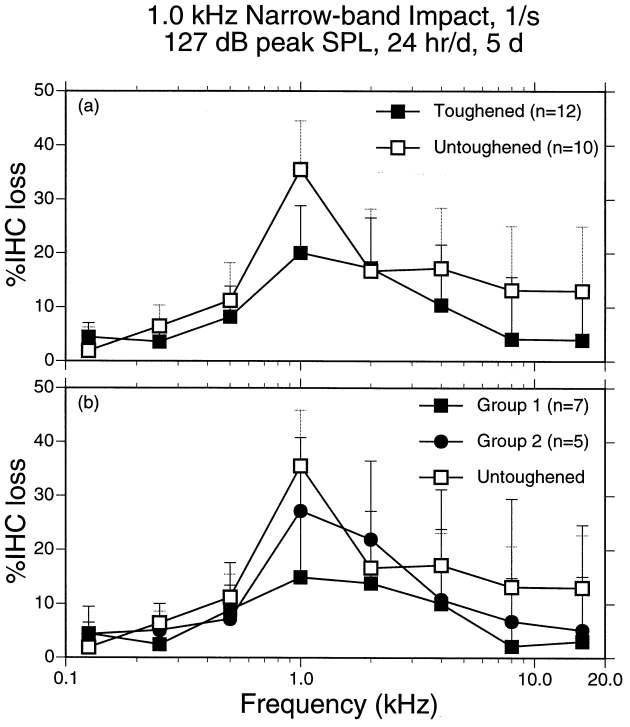

Fig. 7. a: The mean IHC loss over adjacent octave band lengths of the basilar membrane, measured 30 days after the 127 dB peak SPL uninterrupted traumatizing exposure, for the entire group of toughened (■) and untoughened (□) animals. b: A similar presentation of 30 day post exposure IHC loss data but the toughened group has been broken down into subgroups 1 and 2. Group 1 (■) represents those animals whose thresholds did not exhibit a $+TS_R$, while group 2 animals (●) developed a robust TS_R.

4. Discussion

As indicated in Section 1, the 95 dB SPL, 0.5 kHz OBN has frequently been used as a stimulus to produce toughening. The 10 day, 6 h/day paradigm, as seen in Fig. 3, produces a temporary TS of only a few dB at the high frequencies and just under 40 dB in the group 2 animals at 0.5 kHz. This TS recovers in all animals of the experimental group to preexposure values within 2–5 days after the exposure. These results are consistent with those reported by e.g., Subramanian et al. (1993), McFadden et al. (1997), Henselman et al. (1994) and others. The toughening exposure produces no lasting effect on the chinchilla AEP audiogram. Similar interrupted noise exposures, however, have been shown to produce some relatively low level OHC loss and stereocilia damage (Boettcher et al., 1992; Subramaniam et al., 1994).

The amount of toughening produced by this exposure paradigm was, however, variable. An estimate of the TS_R reported in six different published studies that have used the same toughening paradigm is shown in Table 1 where the mean TS_R values are compared to those reported in this paper. The amount of toughening seen in our group 2 animals is consistent with the published data. It is also clear that the group 1 animals constitute a subpopulation that exhibited a very different response to the toughening noise. That is, there was either no toughening or a $-TS_R$. The reasons for the appearance of this subpopulation are not known.

However, it should be noted that other studies in the literature that should have shown some toughening from an interrupted noise exposure did not. For example, based on the results of the toughening experiments referenced in this paper, the interrupted noise exposure paradigms used by Saunders et al. (1977) and by Henderson et al. (1979) should also have produced some evidence of a $+TS_R$. However, as in our group 1 animals, no toughening effect was observed in either of these two studies which are reviewed in more detail in Roberto et al. (1996). Individual animals that appeared to be resistant to toughening were also discussed in Hamernik et al. (1994) where, based on a small sample size and some statistical analysis, they suggested that such subjects might be more susceptible to noise-induced hearing loss. The results in this present paper argue against such a conclusion. Finally, the subset of animals that showed a $-TS_R$ had clean bullae at the time their cochleas were removed. These animals also responded to the traumatic noise, in terms of ATS, PTS and sensory cell loss, the same as the animals that showed a $+TS_R$. These results and observations would argue against middle ear problems being the cause of the $-TS_R$ in this group.

The response of the toughened animals to the ATS producing, 127 dB peak SPL noise presentation, whether taken as a single group or divided into the group 1 and 2 subsets, did not differ from the untoughened control group. Using an interrupted impact noise exposure paradigm to produce a substantial TS_R, Ahroon and Hamernik (1999) showed that for a 1 kHz NBI, 121 dB peak SPL impact noise exposure that produces an ATS, animals that are previously toughened show a large and systematic reduction in ATS. If, however, the ATS producing impact noise exposure is increased in intensity to 127 dB the toughened and untoughened animals showed no statistically significant difference in ATS. The ATS results in this present paper are consistent with the results of Ahroon and Hamernik (1999).

An examination of Fig. 5 indicates that the group exposed to the toughening noise, taken as a whole or broken into subgroups, shows no statistically significant difference in permanent effects on AEP thresholds from the untoughened control group. The best comparison between our results and others is with the study of

Table 1
Mean toughening (TS_R in dB) at the indicated test frequencies reported in the literature and the present study for groups of chinchillas exposed to a 0.5 kHz CF octave band of noise at 95 dB SPL on an interrupted schedule of 6 h/day for 10 days

Frequency (kHz)	TS_R (dB)							TS_R (dB)	
	Reference number							Present study	
	1	2	3	4	5	6	Mean	Group 1	Group 2
	$n=7$	$n=9$	$n=7$	$n=5$	$n=6$	$n=6$		$n=7$	$n=5$
0.5	10	18	19	28	18	-	18	0	22
1.0	19	19	19	25	15	13	18	−5	21
2.0	12	24	22	24	11	14	18	−17	15
4.0	3	18	20	10	−6	−5	8	−17	−5
8.0	−5	4	9	−1	−7	−11	−1	−5	−3
16.0	–	–	10	–	−4	–	3	−3	−1

References: (1) Henselman et al., 1994; (2) Subramaniam et al., 1993a); (3) Subramaniam et al., 1991; (4) Subramaniam et al., 1993b); (5) McFadden et al., 1997; (6) Subramaniam et al., 1994.

Henselman et al. (1994). The same toughening protocol was used and as can be seen from Table 1, their TS_Rs are similar to ours; at 0.5 kHz, our TS_R is 12 dB greater. While both studies used high level transients to produce trauma, the Henselman et al. traumatic exposure was very brief, about a minute in duration. We chose an ATS paradigm to produce trauma because of the relatively stable and consistent effects of such exposures (Carder and Miller, 1972), whereas high level acute impulse noise exposures are notorious for their variability (Hamernik et al., 1991). Despite some similarities between these two studies we were unable to elicit a protective effect on thresholds or sensory cell loss as a result of the toughening exposure while Henselman et al. showed a large protective effect on both the AEP thresholds and the sensory cell population. As with our untoughened group, the sensory cell loss found in the Henselman et al. study was very large in the untoughened animals exposed to the high level noise. Thus in both of these studies the traumatic exposure, although very different, caused a similar loss of sensory cells in the untoughened subjects. The similar level of noise-induced changes in these two studies suggest that any upper limit to a protective effect that might exist should not have been exceeded in our subjects.

A recent paper by White et al. (1998) using a different interrupted noise stimulus to toughen the auditory system also showed no protective effect on PTS when their subjects (gerbils) were exposed to a subsequent traumatic noise. They did, however, show a large reduction in compound TS. Their results parallel those of Ahroon and Hamernik (1999). The discussion presented by White et al. on the lack of agreement between their results and those of Campo et al. (1991) and others that reported protective effects on PTS cannot be improved upon in explaining the lack of a protective effect in our results. A few points might, however, be added. Although the toughening-induced protective effect can last for more than a 30 day interval between toughening and a traumatic exposure (McFadden et al., 1997), our use of a 5 day ATS paradigm to create a relatively stable CTS and reduced variability might, in a sense, 'fatigue' any protective effect. The traumatic exposures reported in the literature are of a relatively short duration. A dissipation of any protective effect because of the duration or severity of the traumatic exposure, however, does not explain the large protective effect on CTS produced by a 5 day exposure to 121 dB peak SPL, 1 kHz NBIs found by Ahroon and Hamernik (1999) without a corresponding protective effect on PTS. Finally, the results of Liberman and Kujawa (1998) suggesting that protection might be the result of a general stress-mediated response, rather than simply a noise-induced effect, needs to be considered.

Acknowledgements

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References

Ahroon, W.A., Hamernik, R.P., 1999. Noise-induced hearing loss in the noise-toughened auditory system. Hear. Res. 129, 101–110.

Ahroon, W.A., Hamernik, R.P., Davis, R.I., 1993. Complex noise exposures: An energy analysis. J. Acoust. Soc. Am. 93, 997–1006.

Boettcher, F.A., Spongr, V.P., Salvi, R.J., 1992. Physiological and histological changes associated with the reduction in threshold shift during interrupted noise exposure. Hear. Res. 62, 217–236.

Campo, P., Subramaniam, M., Henderson, D., 1991. The effect of 'conditioning' exposures on hearing loss from traumatic exposure. Hear. Res. 55, 195–200.

Canlon, B., Borg, E., Flock, A., 1988. Protection against noise trauma by pre-exposure to a low level acoustics stimulus. Hear. Res. 34, 197–200.

Carder, H.M., Miller, J.D., 1972. Temporary threshold shifts from prolonged exposure to noise. J. Speech Hear. Res. 15, 603–623.

Clark, W.W., Bohne, B.A., Boettcher, F.A., 1987. Effects of periodic rest on hearing loss and cochlear damage following exposure to noise. J. Acoust. Soc. Am. 82, 1253–1264.

Davis, H., Morgan, C.T., Hawkins, J.E. et al., 1950. Temporary deafness following exposure to loud tones and noise. Acta Otolaryngol. 88 (Suppl.), 1–57.

Eldredge, D.H., Miller, J.D., Bohne, B.A., 1981. A frequency-position map for the chinchilla cochlea. J. Acoust. Soc. Am. 69, 1091–1095.

Fay, R.A., 1988, Hearing in Vertebrates. Hill-Fat Associates, Winnetka, IL.

Hamernik, R.P., Ahroon, W.A., 1999. Interrupted noise exposures: Threshold shift dynamics and permanent effects. J. Acoust. Soc. Am. 103, 3478–3488.

Hamernik, R.P., Patterson, J.H., Turrentine, G.A., Ahroon, W.A., 1989. The quantitative relation between sensory cell loss and hearing thresholds. Hear. Res. 38, 199–212.

Hamernik, R.P., Ahroon, W.A., Turrentine, G., Davis, R.I., Hsueh, K.D., Lei, S.F., 1991. The effects of blast trauma (impulse noise) on hearing: A parametric study. US Army Medical Research and Development Command, Final Contractor Report ADA 241117.

Hamernik, R.P., Ahroon, W.A., Davis, R.I., Lei, S.F., 1994. Hearing threshold shifts from repeated 6-h daily exposure to impact noise. J. Acoust. Soc. Am. 95, 444–453.

Henderson, D., Hamernik, R.P., Hyson, K., 1979. Hearing loss from simulated work-week exposure to impulse noise. J. Acoust. Soc. Am. 65, 1231–1237.

Henselman, L.W., Henderson, D., Subramaniam, M., Sallustio, V., 1994. The effect of 'conditioning' exposures on hearing loss from impulse noise. Hear. Res. 78, 1–10.

Humes, L.E., 1984. Noise-induced hearing loss as influenced by other agents and by some physical characteristics of the individual. J. Acoust. Soc. Am. 76, 1318–1329.

Liberman, M.C., Kujawa, S.G., 1998. Role of the olivocochlear system in conditioning-related protection. In: Popelka, G.R. (Ed.), Abstracts of the Twenty-First Midwinter Research Meeting. Association for Research in Otolaryngology, St. Petersburg Beach, FL, p. 140.

McFadden, S.L., Henderson, D., Shen, Y.H., 1997. Low-frequency 'conditioning' provides long-term protection from noise-induced threshold shifts in chinchillas. Hear. Res. 103, 142–150.

Miller, J.D., Watson, C.S., Covell, W.P., 1963. Deafening effects of noise on the cat. Acta Otolaryngol. 176 (Suppl.), 1–91.

Mills, J.H., 1973. Threshold shifts produced by exposure to noise in chinchillas with noise-induced hearing losses. J. Speech Hear. Res. 16, 700–708.

Mills, J.H., 1992. Noise-induced hearing loss: Effects of age and existing hearing loss. In: Dancer, A.L., Henderson, D., Salvi, R.J., Hamernik, R.P. (Eds.), Noise-Induced Hearing Loss. Mosby Year Book, St. Louis, MO, pp. 237–245.

Roberto, M., Hamernik, R.P., Ahroon, W.A., Case, C.J., 1996. The effects of primed and interrupted impact noise exposures on hearing loss in the chinchilla. In: Salvi, R.J., Henderson, D., Fiorino, F., Colletti, V. (Eds.), Auditory System Plasticity and Regeneration. Thieme Medical, New York, pp. 165–180.

Saunders, J.C., Mills, J.H., Miller, J.D., 1977. Treshold shift in the chincilla from daily exposure to noise for six hours. J. Acoust. Soc. Am. 61, 558–570.

Subramaniam, M., Campo, P., Henderson, D., 1991. The effect of exposure level on the development of progressive resistance to noise. Hear. Res. 52, 181–188.

Subramaniam, M., Henderson, D., Campo, P., Spongr, V.P., 1992. The effect of 'conditioning' on hearing loss from a high frequency traumatic exposure. Hear. Res. 58, 57–62.

Subramaniam, M., Henderson, D., Spongr, V.P., 1993a. Protection from noise induced hearing loss: Is prolonged 'conditioning' necessary? Hear. Res. 65, 234–239.

Subramaniam, M., Henderson, D., Spongr, V., 1993b. Effect of low-frequency 'conditioning' on hearing loss from high-frequency exposure. J. Acoust. Soc. Am. 93, 952–956.

Subramaniam, M., Salvi, R.J., Spongr, V.P., Henderson, D., Powers, N.L., 1994. Changes in distortion product otoacoustic emissions and outer hair cells following interrupted noise exposures. Hear. Res. 74, 204–216.

White, D.R., Boettcher, F.A., Miles, L.R., Gratton, M.A., 1998. Effectiveness of intermittent and continuous acoustic stimulation in preventing noise-induced hearing and hair cell loss. J. Acoust. Soc. Am. 103, 1566–1572.