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Research Note

TINNITUS AND NEURAL ACTIVITY

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The spontaneous discharge rates of auditory nerve fibers were measured in a group of normal chinchillas and in a group of chinchillas with high-frequency, noise-induced hearing loss. In contrast to normal units, the high-frequency units in the noise-exposed animals tended to have elevated spontaneous discharge rates, high thresholds, and a lack of two-tone inhibition. The change in spontaneous discharge rate across the distribution of nerve fibers is related to models of tinnitus and to human psychophysical data.

Penner (1980) recently described some of the psychoacoustic characteristics of subjects with high-frequency, noise-induced hearing loss and tinnitus. The pitch of the tinnitus was localized to the steeply rising border of the hearing loss. Furthermore, the tinnitus was masked by a band of noise surrounding the frequency of the tinnitus. A forward-masking paradigm showed that there was a loss of suppression (or unmasking) for a probe tone centered in the region of the tinnitus, whereas suppression was present at other frequencies where hearing was normal. Based on these observations, Penner speculated that the loss of the suppression mechanism might result in excess spontaneous activity among the high-threshold units. The "edge" formed by the boundary between high-frequency neurons with high spontaneous rates and other neurons with normal rates could provide the signal for tinnitus. Penner's psychophysical results prompted us to reexamine in more detail previous psychophysical, anatomical, and physiological data obtained from our noise-exposed chinchillas.

METHOD

Four chinchillas were exposed for 5 days to an octave band of noise centered at 4 kHz and at a level of 86 dB SPL. The animals' behavioral thresholds were monitored before, during, and after the exposure to obtain measures of temporary and permanent threshold shift. Approximately 6 months after the exposure, the animals were anesthetized and recordings were made from single VIII nerve fibers. Measurements were made of spontaneous activity, tuning curves, and two-tone inhibition (TTI). Approximately 90–150 units were recorded from each animal. Details of the anatomical, psychophysical and physiological methods can be found in previous reports (Salvi, Hamernik, & Henderson, 1978; Salvi, Perry, Hamernik, & Henderson, 1982).

RESULTS

Figure 1 shows three sets of data from one animal. The top panel shows the loss of outer (OHC) and inner hair cells (IHC) as a function of position in the cochlea and also as a function of stimulus frequency (Eldredge, Miller, Bohne, & Clark, 1977). The middle panel shows the temporary (TTS) and permanent threshold shifts (PTS) measured behaviorally along with an estimate of the permanent threshold shifts of individual nerve fibers. The bottom panel shows the maximum amount of two-tone inhibition observed in each fiber using an excitatory tone at the characteristic frequency (CF) and an inhibitory tone slightly greater than CF.

Several features of the data are important. First, the exposure produces a substantial TTS above 2 kHz but has virtually no effect on lower frequencies. Thus, the low frequencies can be viewed as a control region. Second, there is a high-frequency PTS of approximately 20 dB above 2 kHz and a hair cell lesion in the high-frequency region of the cochlea. Finally, neurons with CFs in the 3- to 8-kHz region have elevated thresholds and show virtually no signs of two-tone inhibition, whereas units higher or lower in frequency show substantial inhibition and normal sensitivity. Note that the loss of two-tone suppression is strongly correlated with the loss in sensitivity. The results of this particular noise exposure were extremely consistent across all four animals.

An interesting comparison can be made between the results shown in Figure 1 and the distribution of spontaneous activity from the four animals shown in Figure 2 and Table 1. A cursory inspection of Figure 2 and the table reveals that most low CF units (< 2.8 kHz) have spontaneous rates of 40–100 spikes per s or rates below 10 spikes per s. Note that there are very few units with rates exceeding 100 spikes per s. This type of bimodal distribution is typical of normal chinchillas (Dallos & Harris, 1978; Henderson, Salvi, & Hamernik, 1982) and

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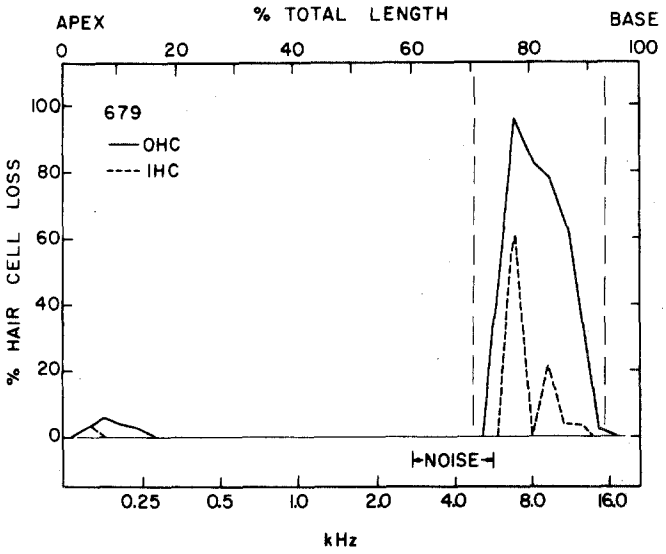
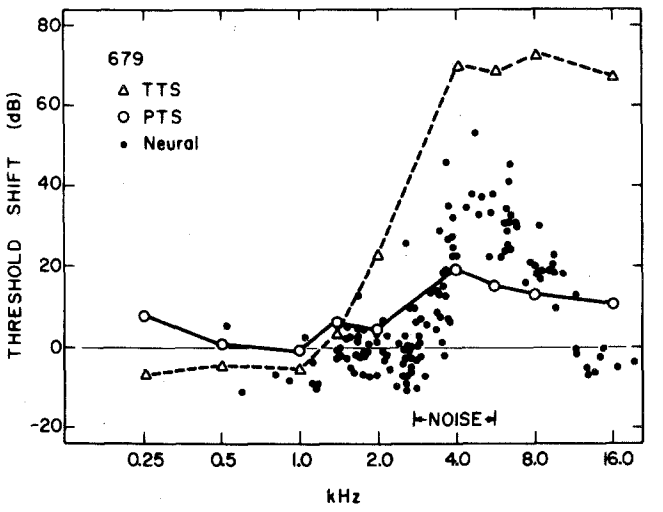
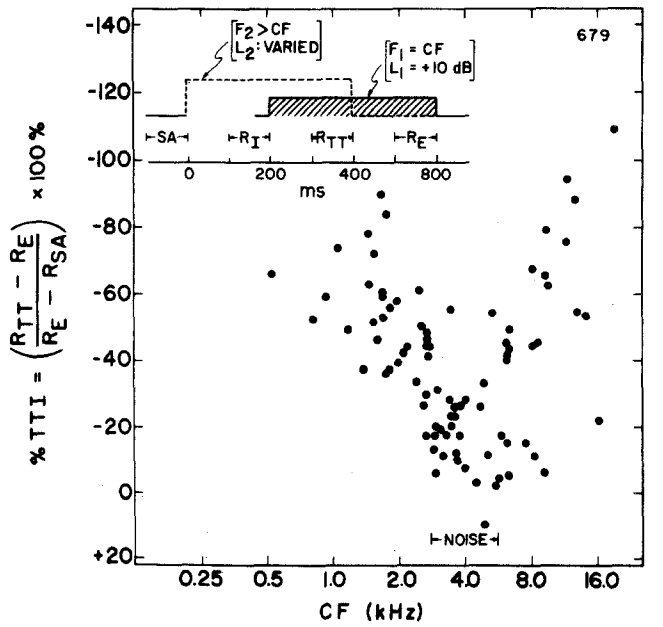


FIGURE 1. Top panel: Cochleogram showing percent outer (solid line) and inner (dashed line) hair cell loss plotted as a function of percent total distance from the apex and as a function of frequency (Eldredge, Miller, Bohne, & Clark, 1977).



Middle panel: Behavioral measures of hearing obtained with a shock avoidance conditioning paradigm. Amount of noise-induced temporary threshold shift measured during exposure is shown by triangles. Degree of permanent threshold shift was measured 6 months postexposure and is shown by open circles. At the end of the behavioral experiment, recordings were made from single auditory nerve fibers. Filled circles show amount of threshold shift (open circles). Solid dots indicate permanent threshold shifts of individual nerve fibers; shifts were estimated by normalizing thresholds of units in noise-exposed animals with those from normal animals.



Bottom panel: Two-tone suppression was assessed by using two tones of 400 ms duration which overlapped in time for 200 ms (see inset). One tone (F_1 = CF) was presented 10 dB above threshold at CF. Frequency of the second tone was varied from 1.1–1.9 times CF and also varied in intensity over a 40- to 80-dB range. The rate during the single-tone interval (R_e) was subtracted from the rate during the two-tone interval (R_{tt}) to obtain amount of suppression. Suppression value was normalized by the driven rate (R_e - R_{sa}) where R_{sa} is the spontaneous rate. Solid dots show maximum amount of two-tone inhibition (TTI) found for each fiber for any combination of frequency (F_2) and intensity. Data are plotted at the unit's CF. The degree of inhibition increases in the negative direction (three panels from Salvi, Perry, Hamernik, & Henderson, 1982).

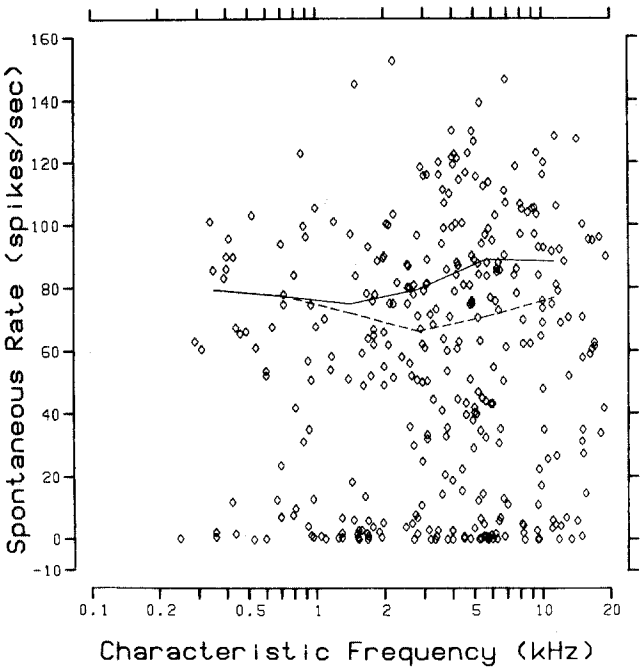


FIGURE 2. Spontaneous discharge rates of single VIII nerve fibers plotted as a function of the characteristic frequency. Data are pooled from four chinchillas exposed to the same noise. (Modified from Salvi, Henderson, & Hamernik, 1983). Mean spontaneous rates of the high spontaneous rate (> 40 spikes/s) units have been plotted across the CF distribution for normal (dashed line) and noise-exposed (solid line) animals, respectively. Note the similarity in rate at low frequencies and the differences at high frequencies.

other mammals (Kiang, 1965; Liberman & Kiang, 1978; Sokolich, 1977). The distribution of spontaneous activity among high CF units (> 2.8 kHz) is distinctly different from that in the low-frequency region. A sizable proportion of the high CF units have spontaneous rates of 10–40 spikes per s, whereas few low CF units have rates within this range. Second, and more importantly, there is a substantial number of high CF units with rates above 100 spikes per s; in fact, one unit (not shown) had a rate of 270 spikes per s. Units with rates above 100 spikes per s are seldom seen in normal animals and were seldom observed among our low CF units. A test for equality of proportions in Table 1 indicated that the frequencies were not distributed randomly (Pearson chi square = 12.988, $df = 3$, $p < .01$).

TABLE 1. Distribution of single units by spontaneous rate and characteristic frequency.

	Spontaneous rate (in spikes/s)		*N*	
CF (in Hz)	*<10*	*10–40*	*40–100*	*>100*
<2800	38	10	65	9
122				
≥2800	50	33	107	43
233				
Total *N* = 355	88	43	172	52

A visual inspection of Figure 2 reveals an abrupt increase in the spontaneous rate near the low-frequency edge of the hearing loss. This trend was analyzed in more detail by computing the mean spontaneous rate for units with CFs in different octave bands. The solid line in Figure 2 shows the mean rate as a function of CF among units with spontaneous rates exceeding 40 spikes per s. Note that the average rate increases near the edge of the hearing loss. The general linear test (Neter & Wasserman, 1974) was performed to compare the spontaneous rates of the low CF units (CF < 2.8 kHz) and the high CF units. The differences between the two groups were statistically significant ($F = 5.39$; $df = 1, 343$; $p < .05$). When only those units with spontaneous rates above 40 spikes per s were used in the analysis, the groups continued to be significantly different ($F = 9.44$; $df = 1, 214$; $p < .05$). The likelihood ratio tests for these two comparisons also were significant with χ^2 values of 4.17 and 7.08, respectively ($df = 1$, $p < .05$). To aid further in the comparison, the data from the noise-exposed animals were compared with spontaneous activity data from a second group of normal chinchillas. The dashed line in Figure 2 represents the mean rate as a function of CF using high spontaneous rate units (> 40 spikes/s) in the group of normal chinchillas. The average rate among the low CF units is nearly the same for both the normal and noise-exposed animals; this is consistent with the view that the low-frequency units in the noise-exposed animals can serve as a control group against which to evaluate the high frequencies. On the other hand, the average spontaneous rate among the high-frequency units in the noise-exposed animals was consistently higher than the rate among the normal units.

To summarize, high-frequency units in the noise-exposed animals have elevated thresholds, show little or no two-tone suppression, and have relatively high spontaneous rates. It is important to note, however, that this is only a correlational relationship and that the increase in spontaneous activity is not necessarily caused by the loss of two-tone suppression or the increase in threshold.

DISCUSSION

A number of mechanisms have been proposed to explain tinnitus, but only recently have neurophysiological data been available to evaluate these hypotheses. One of the most popular explanations for tinnitus has been the notion of elevated rates of spontaneous neural activity due to an irritative lesion in the cochlea. This hypothesis was brought into serious question when Kiang, Moxon, and Levine (1970) and Schmiedt, Zwislocki, and Hamernik (1980) showed that the spontaneous rates of VIII nerve fibers were severely reduced in animals treated with ototoxic doses of Kanamycin. As a consequence, Kiang et al. (1970) proposed an alternative model for tinnitus based on an abrupt change in spon-

taneous rate as a function of CF. This edge effect brought about by the reduction in spontaneous activity presumably would result in an auditory sensation in the absence of any external sound. Our results suggest that acoustic trauma, another agent that affects the cochlea, may create an edge in the opposite way, that is, by increasing the level of spontaneous activity.

Other investigators have reported a tendency toward elevated spontaneous rates following acoustic trauma (Liberman & Kiang, 1978; Schmiedt et al., 1980) and the administration of high doses of salicylates (Evans, Wilson, & Borerwe, 1981). Unfortunately, these studies lacked either behavioral data or comparable human psychophysical results necessary to relate their findings to the perception of tinnitus. Our behavioral and neural results, on the other hand, show some striking parallels with Penner's psychophysical observations. She reported that tinnitus was localized along the edges of the hearing loss in a region where psychophysical suppression was absent. We find an abrupt increase in spontaneous activity near the border of the hearing loss in a region where two-tone inhibition is nearly absent. The parallels between the neural and psychophysical data are intriguing and may bring us a step closer to understanding the neurophysiological mechanism(s) for tinnitus. Although the comparison between tinnitus and the "edge" in the distribution of spontaneous activity is intriguing, it is based only on correlational evidence. Furthermore, the model would have difficulty accounting for tinnitus that is matched to a broad spectrum signal such as a buzz or noise; thus other mechanisms will need to be considered.

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