Response Adaptation of Medial Olivocochlear Neurons Is Minimal

M. C. BROWN

Department of Otology and Laryngology, Harvard Medical School, Harvard–MIT Division of Health Sciences and Technology and Eaton–Peabody Laboratory, Massachusetts Eye and Ear Infirmary, Boston, Massachusetts 02114

Received 21 May 2001; accepted in final form 23 July 2001

Brown, M. C. Response adaptation of medial olivocochlear neurons is minimal. J Neurophysiol 86: 2381–2392, 2001. Response adaptation is a general characteristic of neurons. A number of studies have investigated the adaptation characteristics of auditory-nerve fibers, which send information to the brain about sound stimuli. However, there have been no previous adaptation studies of olivocochlear neurons, which provide efferent fibers to hair cells and auditory nerve dendrites in the auditory periphery. To study adaptation in efferent fibers, responses of single olivocochlear neurons were recorded to characteristic-frequency tones and noise, using anesthetized guinea pigs. To measure short-term adaptation, stimuli of 500 ms duration were presented, and the responses were displayed as peristimulus time histograms. These histograms showed regular peaks, indicating a “chopping” pattern of response. The rate during each chopping period as well as the general trend of the histogram could be well fit by an equation that expresses the firing rate as a sum of 1) a short-term adaptive rate that decays exponentially with time and 2) a constant steady-state rate. For the adaptation in medial olivocochlear (MOC) neurons, the average exponential time constant was 47 ms, which is roughly similar to that for short-term adaptation in auditory-nerve fibers. The amount of adaptation (expressed as a percentage decrease of onset firing rate), however, was substantially less in MOC neurons (average 31%) than in auditory-nerve fibers (average 63%). To test for adaptation over longer periods, we used noise and tones of 10 s duration. After the short-term adaptation, the responses of MOC neurons were almost completely sustained (average long-term adaptation 3%). However, in the same preparations, significant long-term adaptation was present in auditory-nerve fibers. These results indicate that the MOC response adaptation is minimal compared with that of auditory-nerve fibers. Such sustained responses may enable the MOC system to produce sustained effects in the periphery, supporting a role for this efferent system during ongoing stimuli of long duration.

INTRODUCTION

Most sensory neurons adapt their response to constant stimuli. Presumably, this adaptation allows the neurons to produce large responses to transient stimuli and smaller responses to ongoing stimuli. In the auditory nerve, firing rates of fibers adapt in response to a tone burst (Chimento and Schreiner 1991; Delgutte 1980; Javel 1996; Kiang et al. 1965; Müller and Robertson 1991; Nomoto et al. 1964; Rhode and Smith 1985; Smith 1979; Smith and Zwislocki 1975; Westerman and Smith 1984; Yates et al. 1985; Young and Sachs 1973). Adaptation in the auditory nerve follows a multi-component time course: 1) rapid adaptation over the first few milliseconds (Chimento and Schreiner 1991; Westerman and Smith 1984), 2) short-term adaptation over about 50–100 ms (Chimento and Schreiner 1991; Müller and Robertson 1991; Rhode and Smith 1985; Westerman and Smith 1984), 3) long-term adaptation over several seconds (Javel 1996), and 4) very long-term adaptation over several minutes (Javel 1996; Kiang et al. 1965). It is likely that rapid and short-term adaptation arise from processes at the synapse between the hair cell and auditory-nerve fiber, because although the fiber’s discharge adapts, receptor potentials of inner hair cells are sustained over tens of milliseconds (Goodman et al. 1982; Russell and Sellick 1978). Long-term adaptation in nerve fibers may also result from synaptic processes (Javel 1996). Such processes probably involve depletion of neurotransmitter at the hair cell/nerve fiber synapse (Furukawa et al. 1978; Norris et al. 1977), although their exact nature remains to be determined.

Olivocochlear (OC) neurons are efferent neurons that arise in the brain stem and project to the cochlea. In the cochlea, medial (M) OC neurons innervate outer hair cells (reviewed by Warr 1992). Their action on outer hair cells probably controls the dynamic range of the cochlea, reduces the effects of noise masking, and protects the cochlea from damage due to acoustic overstimulation (Geisler 1974; Kawase et al. 1993; Meric and Collet 1994; Rajan 1995; Wiederhold and Kiang 1970; Winslow and Sachs 1988; reviewed by Guinan 1996). MOC neurons can perform these functions because they respond to sound as part of a reflex. In response to sound, typical latencies of MOC neurons are 5–50 ms (Brown 1989; Liberman and Brown 1986; Robertson and Gummer 1985), and typical effects at the outer hair cells are seen about 50–100 ms later (Wiederhold and Kiang 1970). Because of these relatively long times, it seems unlikely that the MOC system could alter the response of the cochlea to brief sounds with durations less than about 100 ms. For example, MOC protection from overstimulation is not likely for short-duration sounds like a gunshot. Rather, MOC protection has been demonstrated for sound exposure durations of minutes (Rajan 1995; Reiter and Liberman 1995) to hours (Kujawa and Liberman 1997; Zheng et al. 1997a,b).

If MOC effects are most functionally significant for long-duration sounds, it is important to consider response adaptation of MOC neurons. For instance, MOC effects are likely to be lessened if the firing rates of MOC neurons adapt over time. This logic follows from studies where the MOC neurons are stimulated electrically to elicit protection; in such studies de-
creasing the stimulation rate from 100 to 50 shocks/s approximately doubles the damage, as measured by the threshold shift 30 min after an acoustic overstimulation (Rajan and Johnstone 1988). Numerous other data indicate that decreasing MOC stimulation rates from the optimal 200–400 shocks/s can greatly decrease other effects of MOC neurons on peripheral responses to sound (Brown and Nuttall 1984; Desmedt 1962; Gifford and Guinan 1987; Konishi and Slepian 1971). However, our knowledge of whether sound-evoked MOC firing decreases over time is limited, since studies of MOC adaptation characteristics have not been made. Knowledge of such characteristics would be useful; for example, to predict the exposure durations for which MOC-mediated protection is most robust. Similar knowledge would also help predict the sound durations for which the MOC system plays a role in adjusting the dynamic range of the cochlea and in reducing the effects of noise masking.

In this study, we measured the adaptation characteristics of single MOC neurons in response to sounds of 500 ms or 10 s duration. We compare these characteristics to those of auditory-nerve fibers recorded in the same preparations. These nerve fibers provide input to the brain and form the initial portion of the MOC reflex. Differences between nerve fiber and MOC adaptation reflect the central changes in response within the MOC reflex pathway. Our results demonstrate that MOC response can be relatively constant with time, far more constant than responses of the auditory nerve, and more constant than many neurons in the cochlear nucleus and superior olivary complex (Boettcher et al. 1990; Finlayson and Adam 1997; Palombi et al. 1994; Shore 1995). A preliminary version of the results has been presented (Brown and Duca 1998).

METHODS

Experimental preparation

A total of 24 albino guinea pigs, of either sex, were used as experimental animals. The methods for surgery and recordings are described elsewhere (Brown 1989). All surgical procedures were in accordance with the National Institutes of Health guidelines for the care and use of laboratory animals. For physiological recordings, guinea pigs were anesthetized with a combination of pentobarbital sodium (Nembutal; 15 mg/kg ip) and Innovar-Vet (0.5 ml/kg im, each ml of Innovar-Vet contains 0.4 mg of fentanyl and 20 mg of droperidol) or with a combination of urethan (1,500 mg/kg ip), fentanyl (0.2 mg/kg im), and droperidol (10 mg/kg im). Additional doses of anesthetics were administered as needed to eliminate the toe-pin chase reflex. Sound stimuli were produced by half-inch condenser microphones coupled to the ear canal in a closed speculum assembly similar to that of Evans (1979). Sound pressure was measured with additional microphones fitted with probe tubes that were advanced within 1 mm of the tympanic membrane. The sensitivity of hearing was measured by microphones fitted with probe tubes that were advanced within 1 mm of the tympanic membrane. The spiral ganglion, which contains the cell bodies of the auditory-nerve fibers, and which is located in the central core or modiolus of the cochlea, was exposed through scala tympani of the cochlear basal turn as described previously (Robertson and Gummer 1985; Sellick and Russell 1979). This surgery was accomplished with minimal alterations in CAP sensitivity (<5–10 dB) across the frequency range tested, otherwise the animal was excluded from this study.

Single-unit recordings and response measures

Single-fiber recordings of MOC neurons were made from the spiral ganglion in the basilar turn (Brown 1989), where MOC axons travel in the intraganglionic spiral bundle. MOC neurons were identified by their regular interspike intervals, long latencies (>5 ms) in response to search stimuli (binaural noise bursts), and the fact that some responded only to monaural contralateral stimulation. Units with these types of responses have been confirmed to be MOC neurons that innervate outer hair cells (Brown 1989; Robertson and Gummer 1985), whereas axons of lateral olivocochlear neurons are probably too thin to be recorded. In contrast, auditory-nerve fiber recordings were identified by their irregular firing patterns, their short latencies, and their response exclusively to ipsilateral stimulation. Auditory-nerve fibers recorded from the spiral ganglion all had high characteristic frequencies (CFs, 12–17 kHz) because the recording site was located in the lower basal turn. Thus to obtain other fibers with lower CFs, some recordings were made from the auditory nerve as accessed through an opening in the modiolus (Alder and Johnstone 1978). In contrast, MOC neurons recorded from the spiral ganglion had a variety of CFs because MOC axons spiral through the recording site en route to their terminations at diverse cochlear locations.

Before adaptation was measured, it was necessary to characterize the MOC neurons based on their response properties. First, noise bursts were presented monaurally to determine each neuron’s response type (Lips units respond to stimuli in the ipsilateral ear, Contra units respond to stimuli in the contralateral ear, and Either Ear units respond to stimuli in either ear). A tuning curve was then determined using an automated procedure (Kiang et al. 1970). The CF and threshold at CF were determined from the tuning curve. To measure response over time, peristimulus time (PST) histograms were obtained in response to CF tone bursts or noise bursts of 500 ms or 10 s duration (50% duty cycle). Histograms for 500 ms were obtained with 50–100 burst presentations, and those for 10 s were obtained with 5–15 burst presentations. Histogram binwidths were 5 or 100 ms, respectively (each histogram contained 200 bins, and these bins encompassed a total time of 1,000 ms or 20 s). Sound burst rise-fall time was always 2.5 ms. Noise and tone levels are specified in dB SPL. For level functions, PSTs were taken at increasing levels with steps of 10 dB. Spontaneous rate (SR) was estimated by averaging the last 10 bins of the PST histogram (at the end of the “off time” when there was no sound stimulus). In a few neurons, “afterdischarge” activity appeared in the off-time in response to moderate and high level bursts (Brown 1989; Liberman and Brown 1986). This activity was not used for the curve fits nor was it counted as SR; rather, SR for these neurons was measured during a 10-s period of silence.

Curve fits to rate equations

For studies of short-term adaptation, the PST data for 500-ms bursts were fit by an equation that expresses the rate as the sum of a declining exponential function plus a steady-state rate

\[ R(t) = R_A e^{-A t} + R_{SS} \]

where \( R(t) \) is the rate at time \( t \), \( R_A \) is the short-term adaptation subcomponent of rate, \( T_a \) is the time constant of short-term adaptation, and \( R_{SS} \) is the steady-state subcomponent of rate.

The starting bin for each fit was determined individually for each PST because MOC responses can have significant and variable latencies (Brown 1989; Liberman and Brown 1986). For each PST, several fits with different starting bins were tried, and the rates predicted by the fits were compared with the actual peak-by-peak average rate (\( \bullet \)). The fit that most closely approximated the average rate was chosen (e.g., for the PST of Fig. 1 the fit began with the 4th bin); this fit was used for the data and for all the data beginning with this bin and including a total of 100 bins, so that a “response window”
Our data set included a total of 27 MOC neurons and 20 auditory-nerve fibers from 15 guinea pigs that were studied with bursts of 500 ms duration, and a total of 19 MOC neurons and 14 auditory-nerve fibers from 14 guinea pigs studied with bursts of 10 s duration. Statistical tests were t-tests performed at the 5% level of significance.

RESULTS

Short-term adaptation for stimuli of 500 ms duration

MOC neurons showed a small amount of adaptation in response to constant stimuli of 500 ms duration. An example PST histogram from one neuron is shown in Fig. 1. The histogram has peaks that reflect the regular firing, or chopping, pattern of these neurons. One method of measuring the firing rate over time is to count the number of spikes in each chopping interval and divide by the time from the beginning to the end of the interval, thus obtaining an average rate for each chopping interval (dots on Fig. 1). For the first chopping interval, this rate was 11.8 spikes/s, and for the last interval it was 8.4 spikes/s, indicating a decrease in firing to 71% of the original rate, or conversely, an adaptation of 29%. An inspection of the PST (Fig. 1) indicates that most of this adaptation takes place within approximately 125 ms from stimulus onset. The decrease in firing will therefore be called short-term adaptation because it occurs on a time scale similar to the short-term adaptation of auditory-nerve fibers (Chimento and Schreiner 1991; Westerman and Smith 1984), and to distinguish it from long-term adaptation over the time course of 10 s that will be discussed later.

The PST data were fit by an equation that expresses the rate as a sum of two subcomponents, a short-term adaptation that decays exponentially with time and a steady-state rate that is constant with time (Eq. 1 in METHODS and on Fig. 1). The best-fit curve is illustrated by the heavy line on the figure, and the parameters are given at the top of the figure. This fit accurately captures the firing rate measured during each chopping interval (dots) as well as the general outline of the PST. The steady-state rate, $R_{SS}$, can be thought of as a combination of a driven steady-state rate, $R_{DSS}$ plus a spontaneous rate, $SR$, or mathematically, $R_{SS} = R_{DSS} + SR$. Like most MOC neurons, the $SR$ for the neuron shown in Fig. 1 was zero, so $R_{SS}$ was equal to $R_{SS}$. Decaying exponential fits are also shown for four other MOC neurons in the top row (A–D) of Fig. 2; only one of these neurons (D) had spontaneous activity. For curve fits for all 27 MOC neurons in our sample, the subcomponent of the rate due to short-term adaptation, $R_A$, averaged $15.0 \pm 2.5$ (SE) spikes/s, and the average $R_{DSS}$ was $31.6 \pm 2.4$ spikes/s. The sound levels used to collect these data were bursts between 65 and 95 dB SPL; the effects of level are considered below.

The curve fits can be used to calculate the amount of short-term adaptation on a percentage basis, which is defined as the decline in rate from the initial rate to the steady-state rate, normalized by the initial rate (Eq. 2 in METHODS). For the neuron illustrated in Fig. 1, the fit predicted a short-term adaptation of 32%, very close to the 29% adaptation obtained from measuring the rates during the first and last chopping intervals. Calculation of adaptation using the fit produces a slightly higher percent since a higher initial rate (numerically $R_A + R_{DSS}$) is used in the calculation, whereas calculation of adaptation by measuring the rate during the first chopping

\[
\% \text{Short-term Adaptation} = \left( \frac{R_i - R_f}{R_i} \right) \times 100\% \quad (3)
\]

where $R_i$, the initial rate, is the average rate over the period from 0.2 to 1.2 s after stimulus onset, a period chosen to be after the decay of short-term adaptation, and $R_f$, the final rate, is the average rate over the period from 9 to 10 s (these measurement windows are shown in Fig. 6A). Spontaneous rate was subtracted from the rates before the calculation.
FIG. 2. PST histograms and curve fits that demonstrate the smaller adaptation in MOC neurons (A–D) than in auditory-nerve fibers (E–H). Responses are to 500-ms duration bursts, arranged in order of increasing characteristic frequency (CF). In each histogram, a curve has been fit to the decaying exponential function for short-term adaptation (see Fig. 1); the percent short-term adaptation and time constant predicted by the best fits are indicated on each histogram. Also on each histogram are the CF, the MOC response type as defined by which ear excited the unit, and the spontaneous rates (SR) in spikes/s. The stimuli were as follows: A, 60 noise bursts at 85 dB SPL; B, 60 tone bursts at 64 dB SPL; C, 50 noise bursts at 85 dB SPL; D, 60 tone bursts at 95 dB SPL; E, 50 tone bursts at 60 dB SPL; F, 50 tone bursts at 70 dB SPL; G, 100 tone bursts at 80 dB SPL; H, 50 tone bursts at 80 dB SPL. Tone burst frequencies were always at the fiber’s CF.
interval (about 25 ms for Fig. 1) uses an average rate over the first chopping interval. It could be argued that a high initial rate predicted by the fit does not represent the true rate in the first histogram bins (Fig. 1); although true, this argument does not greatly change the percent adaptation. For the neurons illustrated in Fig. 2, the percent short-term adaptation from the fits are indicated on each panel; these range from 23 to 31%. For all MOC neurons, the average percent adaptation was 30.9 ± 2.1.

Decaying exponential equations were also fit to PST data from auditory-nerve fibers (Fig. 2, E–H). For the 20 auditory-nerve fibers of our sample, the average percent adaptation was 62.6 ± 2.9. This adaptation was significantly greater than the average for MOC fibers (30.9%), using a t-test (P = 0.001). For nerve fibers, alternate methods for computing percent adaptation did not change the values much. The alternate method of measuring the percent change from the onset rate (the 1st bin) to the steady-state rate (the average of the last 10 bins in the response window) yielded an average of 65.6%, a very similar value to that obtained using the curve fits (62.6%). To explore whether the higher adaptation in auditory-nerve fibers could be made artificially as low as MOC neurons by constraining the measurement bins to intervals as long as the MOC chopping intervals, auditory-nerve firing was artificially binned into long intervals (20 ms) and adaptation was measured again. This test only changed the average nerve-fiber adaptation by 3.2%, having most influence on fibers with very short time constants of adaptation (e.g., Fig. 2G). All of these methods are likely to underestimate the true amount of adaptation in auditory-nerve fibers because relatively coarse bin-widths (5 ms in our data) do not capture the true onset rate that, unlike MOC neurons, is typical of nerve fibers (Chimento and Schreiner 1991; Müller and Robertson 1991; Westerman and Smith 1984). Indeed, percent adaptations for nerve fibers average 84% when calculated from published data obtained with finer binwidths and with equations that two exponential components of decay. Conversely, MOC data taken with finer binwidths do not show high onset firing (Brown 1989; Liberman and Brown 1986; Robertson and Gummer 1985), making it very likely that our methods have accurately estimated the amount of MOC adaptation.

For all neurons recorded, the percent short-term adaptation and the time constant of adaptation, computed from the curve fits, are plotted against the fiber CF in Fig. 3. MOC neurons clearly have the lowest percent adaptations throughout the CF range (A), although the adaptation of some low-SR nerve fibers can be equally low (squares on Fig. 3A, PSTs of Fig. 2, F and H) as previously reported (Müller and Robertson 1991; Rhode and Smith 1985). In contrast to the percent adaptation, time constants (Fig. 3B) are not significantly different: the average MOC time constant was 46.7 ± 5.1 ms and for the auditory-nerve fibers it was 44.4 ± 7.3 ms. There was little CF dependence of percent adaptation or time constants, for either MOC neurons or auditory-nerve fibers. There was also little difference in these measures between the MOC response types, which in our sample are Ipsi units (●, Fig. 3) and Contra units (▲, Fig. 3). Adaptation also did not obviously depend on whether tones or noise were used as the stimulus. In the data of Fig. 3, 17 of the neurons were stimulated with noise, and the other 10 points were stimulated with tones. The average percent adaptation measured with noise (29.9 ± 2.9, n = 17) was not significantly different from that measured with tones.
(32.6 ± 2.8, n = 10). In addition, one neuron was studied with both tones and noise at a variety of levels; the percent adaptations and time constants were overlapping for the two stimuli. Finally, present data (not shown) do not reveal any dependence of short-term adaptation on MOC neuron threshold at CF (average 40, range 16–75 dB SPL) or on MOC neuron spontaneous rate (average 1.9, range 0–24.6 spikes/s).

After the tone burst ends, auditory-nerve fiber spontaneous activity is depressed transiently but returns with a time course similar to that of short-term adaptation (Fig. 2, E and G) (Harris and Dallos 1979; Kiang et al. 1965). We observed a similar depression and return of spontaneous activity in the five MOC neurons with significant spontaneous activity; one example is shown in Fig. 2D. Spontaneous activity in MOC neurons usually returned in peaks synchronized to the stimulus offset (Fig. 2D).

**Level dependence of short-term adaptation**

The level dependence of short-term adaptation and other measures of rate are shown for four MOC neurons in Fig. 4. The measured average rate (●) is a count of all the spikes in the “response window” of 500 ms and is the value usually plotted in level functions. This measured rate is a driven rate because...

![Graph](http://jn.physiology.org/)

**FIG. 4.** Rate vs. level functions for 4 MOC neurons to demonstrate the level dependence of the rate subcomponents. The 5 rates plotted are as follows: 1) measured average rate, the total driven rate averaged during a 500-ms time window that was shifted to account for the neuron’s latency; 2) the calculated average rate (from integrating over 500 ms the best-fit equation, Eq. 1 in METHODS); 3) the short-term adaptation (RA from the equation); 4) the driven steady-state rate (RSS = RS − SR from the equation); and 5) the onset rate, the rate from the equation at time 0 (RA + RSS). Calculated rates are not available for the points taken at the lowest levels because curve fits were not accurate when the driven rates were very low. Stimuli were CF tone bursts.
spontaneous rate has been subtracted. Calculated average rates from the exponential fits (○, Fig. 4) closely match the measured average rate, indicating that the fits closely reflect the PST data. Also plotted on Fig. 4 are the two terms from the fit, the short-term adaptation ($R_A$) subcomponent of the rate and the steady-state rate ($R_{DSS}$) subcomponent, and their sum, the onset rate. $R_A$ is smaller than the other components, and it increases with level in three of the four neurons shown (A, C, and D). $R_{DSS}$ also increases with level, closely tracking the average rate and having the same large dynamic range that is typical of the measured average rate for MOC neurons (Brown 1989; Brown et al. 1998; Liberman and Brown 1986; Robertson and Gummer 1985). Similar to data from auditory nerve fibers (Westerman and Smith 1984), in MOC neurons $R_A$ increases fairly linearly with $R_{DSS}$ (data not shown). Thus when short-term adaptation is computed on a percentage basis ($R_A$ divided by $R_A + R_{DSS}$), there is little dependence on level (Fig. 5A). The time constants also show little overall dependence on level (Fig. 5B), although there is some variability from neuron to neuron in these data.

**Adaptation for stimuli of 10 s duration**

The adaptation characteristics of MOC neurons were also measured in response to much longer stimuli (10 s duration). For these long bursts, example PST histograms from MOC neurons and auditory-nerve fibers are shown in Fig. 6. On the time scale illustrated, the MOC neuron’s latency to response and its short-term adaptation take place within the first two bins of the histograms (1st 0.2 s). For MOC neurons, there were almost no further rate changes. To compare MOC behavior with that of auditory-nerve fibers, a simple measure of long-term adaptation was defined using two measurement windows that are shown by brackets on Fig. 6A. Long-term adaptation (Eq. 3 in METHODS) was defined as the normalized decline in rate from an initial rate, $R_i$, which is measured over a 1-s period after short-term adaptation had decayed, to a final rate, $R_f$, which is measured over the final 1-s period of the burst on time. For the histograms shown in Fig. 6, the long-term adaptation ranged from −1 to 6% for MOC neurons (A–D). A small negative value of adaptation, −1% seen in D, indicates that the rate shows a small increase during the 10 s burst. In Fig. 6, auditory-nerve fibers (E–H) have obvious positive adaptations over the 10-s burst. Their values for percent long-term adaptations range from 16 to 180%. The one fiber with an adaptation of over 100% reflects the fact that the rate during the stimulus has fallen below the spontaneous rate. Some fibers with similarly high adaptations were reported by Javel (1996). Our definition of long-term adaptation uses a broad time window (1 s) for comparing rate at the beginning versus the end of the burst. An inspection of Fig. 6 indicates that using an earlier subinterval for the initial rate (e.g., the period between 0.2 to 0.7 s rather than between 0.2 and 1.2 s) would probably not change the measure of adaptation for MOC neurons but would increase it for auditory-nerve fibers.

Although there was little long-term adaptation in MOC neurons, there was sometimes a suppression and a slow recovery of spontaneous activity after the burst ended. This recovery occurred over a time course of several seconds (Fig. 6B), a pattern seen in three of the six MOC neurons with spontaneous activity that were tested with 10-s bursts. The spontaneous activity in two of the six neurons returned within a half-second of the offset. In the final neuron, there was no obvious decline in spontaneous activity (Fig. 6D), and for its response to 500-ms bursts, the spontaneous activity was synchronized in peaks locked to the offset of the burst (shown for another neuron in Fig. 2D).

The percent long-term adaptation is shown for MOC neurons and auditory nerve fibers in Fig. 7. MOC neuron long-term adaptation is almost always less than that of auditory-nerve fibers and is near zero in the majority of MOC neurons. The average percent long-term adaptation for MOC neurons was 2.9 ± 1.9% (for 19 neurons), whereas the average for auditory nerve fibers was 35.4 ± 11.6% (for 14 fibers), a difference that was statistically significant. Similar to the data for short-term adaptation, MOC neuron long-term adaptation had little CF dependence nor did it differ between Ipsi and Contra units (Fig. 7). For the eight neurons tested with both noise and tones, there was also no significant difference in long-term adaptation for the two stimuli (data not shown). For auditory-nerve fibers, there is little CF dependence, but there is a tendency for high-SR rates to adapt the most (although there is considerable overlap for fibers of different SRs).

**FIG. 5.** Level functions for percent short-term adaptation (A) and time constant (B) for MOC neurons, showing the level independence of these measures. Each line shows data from 1 neuron; functions for 6 Ipsi units are shown in solid lines and 4 Contra units in interrupted lines. The stimuli were CF tone bursts.
FIG. 6. PST histograms demonstrating the constant rate of MOC neurons (A–D) and the long-term adaptation of auditory-nerve fibers (E–H). Responses were to 10-s bursts and are arranged in order of increasing CF. The typical chopping pattern in MOC neurons is not preserved with the coarse time bins (100 ms/bin) illustrated here. The long latency (e.g., 50 ms) of some MOC neurons can result in a small number of spikes in the 1st bin (A). A: brackets indicate the measurement windows (0.2–1.2 s for $R_1$, and 9–10 s for $R_2$) used to compute long-term adaptation. Each panel also shows the values for percent long-term adaptation (see Eq. 3), CF, response type (for MOC neurons), and spontaneous rate (in spikes/s). The stimuli were as follows: A, 10 tone bursts at 75 dB SPL; B, 7 noise bursts at 65 dB SPL; C, 10 tone bursts at 85 dB SPL; D, 5 noise bursts at 75 dB SPL; E, 13 tone bursts at 60 dB SPL; F, 12 tone bursts at 60 dB SPL; G, 15 tone bursts at 60 dB SPL; H, 15 noise bursts at 65 dB SPL.
neurons (\(\text{h} \text{ and } 180\%\) long-term adaptation). One auditory-nerve fiber had an adaptation off the scale used here (arrow: nerve fibers). The stimuli were presented at levels between 60 and 85 dB SPL.

Comparison of MOC and auditory-nerve adaptation

Adaptation characteristics of MOC neurons and auditory-nerve fibers differ in several ways. For short-term adaptation that is seen over about 100 ms after stimulus onset, the amount of adaptation seen in MOC neurons is approximately half that seen in nerve fibers. For the firing pattern over several seconds, there is almost no long-term adaptation of MOC response, even though auditory-nerve fibers in the same preparations showed substantial long-term adaptation. The other types of adaptation seen in the auditory nerve were not studied: rapid adaptation (Chimento and Schreiner 1991; Westerman and Smith 1984) would be difficult to study in MOC neurons because it would take place within the first peak of the PST histogram. Very long-term adaptation has yet to be systematically investigated, although minimal declines in rate in response to continuous tones have been reported for a few MOC neurons (Liberman and Brown 1986).

Many MOC neurons have large dynamic ranges, however, which are not typical of auditory-nerve fibers. Present data show that the dynamic range is usually large both for the small adaptive and larger steady-state components of the rate. Yet overall in both auditory-nerve fibers (Westerman and Smith 1984) and in MOC neurons, the percent short-term adaptation and its time constant do not generally depend on level (Fig. 5). Also like earlier studies of nerve fibers (Westerman and Smith 1984), we found little dependence of short-term adaptation on CF for MOC neurons, and in addition we found little adaptation difference between Ipsi and Contra MOC neurons. In a previous study of nerve-fiber adaptation (Yates et al. 1985), short-term adaptation was reported to have a linear rather than exponential decay. Our fit to nerve fiber data used a single exponential; this method is simplified but appropriate given the coarse binwidth of the PST histograms. The decay is better fit by two exponentials that reflect rapid as well as short-term adaptation (Chimento and Schreiner 1991; Javel 1996; Westerman and Smith 1984). MOC neuron adaptation, however, was well fit by a single exponential process.

Although we have described the adaptation occurring within a stimulus; a related issue is the effect of repeating a series of bursts. This question has been investigated for repeated bursts of 50 ms duration with a 50% duty cycle, which, due to the slow chopping in MOC neurons, evoke only one or two spikes per burst. For repeated bursts, there is little habituation of spike rate over a time course of seconds; that is, the response to the 10th burst is the same as the response to the 1st burst (Brown et al. 1998; Liberman and Brown 1986). Apparently, short-term adaptation is so small and so quick to recover that responses to later bursts are not different from that to the initial burst. It is likely, however, that anesthetic state plays some role in the pattern of MOC response. Thus some neurons in deeply anesthetized cats “build up” their response; that is, they only begin to respond to repeated tone bursts after several tone bursts have been presented (Liberman and Brown 1986).

Long-term adaptation was almost nonexistent in MOC fibers; this finding is also evident from an inspection of a few figures of early MOC recordings in decerebrate cats (Fex 1962, 1965). Results of the present study show that in the same preparations where MOC response is constant, long-term adaptation in auditory-nerve fibers (Javel 1996; Kiang et al. 1965) can be prominent. Long-term adaptation in nerve fibers can be fit with a decaying exponential function with a time constant of about 3.6 s (Javel 1996). Average amounts of long-term adaptation for high-SR nerve fibers were about 40%, which is similar to that found in the present study. In the present study, there was a tendency for the rates of high-SR fibers to adapt the most (although there is considerable overlap for fibers of different SRs). Javel’s study also showed considerable overlap, but there was a tendency for low-SR fibers to adapt more than those with medium and high spontaneous rates. The reason for this difference in tendencies is not known.

Very long-term adaptation is also present in auditory-nerve fibers with time constants of minutes. Although not studied here, an earlier report indicates that for the few MOC neurons studied, there was a small adaptation of roughly 10% over about 10 min (Liberman and Brown 1986). This percentage is
How is adaptation minimized in MOC neurons?

This study has demonstrated large differences in the amount of adaptation in MOC neurons and auditory-nerve fibers, for both short- and long-term adaptation. This difference is found for units within the same preparation, demonstrating that it is unlikely to be due to factors such as recording methods, differences in the state of the experimental preparation or species differences. The difference in adaptation is interesting because the auditory-nerve fibers provide the input to the MOC reflex. Thus the decline in input provided by the nerve fibers must be compensated for by elements within the MOC reflex at more central locations. The location of these elements could be within the interneurons of the pathway leading to the MOC neurons or possibly within the MOC neurons themselves.

The identities of the interneurons in the MOC reflex pathway are not precisely known. These interneurons must include neurons of the cochlear nucleus, because this nucleus is an obligatory synaptic site for the auditory nerve. The interneurons are likely located in the ventral cochlear nucleus (VCN), either in the posterior subdivision of the VCN (de Venecia et al. 2001; Thompson and Thompson 1991; Warr 1982) and/or in the anterior subdivision (Robertson and Winter 1988; Ye et al. 2000). Some VCN neurons show little adaptation. In particular, little short-term adaptation is seen in “Sustained” chopper units (Blackburn and Sachs 1989), and in low-intensity Chopper units, which are units reported to have a chopping pattern only at low sound levels (Shore 1995). Certainly, those VCN neurons with relatively sustained rates are candidates to be the MOC reflex interneurons. Some of this sustained cochlear nucleus firing might be generated by convergence of low-SR auditory-nerve fibers, which have been demonstrated to have fairly sustained responses (Müller and Robertson 1991; Rhode and Smith 1985). Indeed, preferential input to the MOC reflex by low-SR auditory-nerve fibers has been previously suggested on the basis of correlation of thresholds at CF in cat data (Liberman 1988), although similar data in guinea pig suggest input from high-SR fibers (Brown 1989). From the cochlear nucleus, the interneurons may directly project to the MOC neurons, as suggested by the short group delays and the relatively peaked shape of the modulation transfer functions of MOC neurons (Guummer et al. 1988).

The sustained pattern of MOC firing, however, could also result from changes at the level of the MOC neurons themselves. The MOC firing patterns reflect the number and position of inputs as well as the membrane properties of the neuron. For instance, even with adapting inputs like auditory-nerve fibers, modeling studies of the cochlear nucleus show that relatively sustained postsynaptic firing can be generated by positioning inputs on the distal dendrites, since dendritic filtering exerts a low-pass characteristic at the soma (Banks and Sachs 1991). Likewise, MOC neurons have long dendrites (Brown 1993) and receive most of their sparse input onto these dendrites (Adams 1996; Spangler et al. 1986). Such anatomy could transform an adapting input into a more sustained response, assuming a long membrane time constant for the dendrites of the MOC neuron. In fact, long time constants could explain the observation that MOC units do not typically fire for brief stimuli like clicks or short-duration (<10 ms) tone bursts, indicating that a long summation of inputs is necessary for a response (Liberman and Brown 1986). Long time constants are also consistent with the unusually long latency of response of MOC neurons at low sound levels, which, at levels near threshold, can be as long as 60 ms (Brown 1989; Liberman and Brown 1986; Robertson and Gummer 1985). Such latencies suggest that a long summation of inputs may be necessary to generate a response. A time constant of tens of milliseconds could account for the minimal short-term adaptation of MOC neurons, but is unlikely to account for the almost complete lack of long-term adaptation since membrane time constants would not be expected to be on the order of seconds. Rather, an additional element has to make up for the input lost by long-term nerve-fiber adaptation. Finally, although recordings from the superior olivary complex indicate that neurons have large response adaptation (Finlayson and Adam 1997), these neurons were probably located in the two main nuclei of the complex, the medial and lateral superior olives, rather than the peri-olivary regions where MOC neurons are located.

Relevance of minimal adaptation for MOC function

MOC function during long-duration sounds would be effective, given relatively nonadapting responses and relatively non-adapting peripheral effects. Minimal adaptation has been demonstrated in the present study. Peripheral effects have been shown to be sustained in earlier studies. One peripheral effect of MOC neurons, reduction in firing of auditory-nerve fibers, can be relatively constant when MOC firing is produced by direct electrical stimulation of the OC bundle in the brain stem (Wiederhold and Kiang 1970). This reduction in nerve-fiber firing can be observed over a period of tens of seconds, although there is some decrease in such effects for high-CF fibers in the first few seconds of stimulation. These results, coupled with the lack of long-term adaptation observed in the present study, suggest relatively constant effects on the MOC targets when this efferent system is activated by sound. Another peripheral effect of MOC neurons, protection from acoustic overstimulation, is seen in paradigms where the sound exposures are hours in duration (Kujawa and Liberman 1997; Zheng et al. 1997a,b), suggesting a sustained MOC response over even longer intervals. The minimal adaptation of MOC neurons and their sustained peripheral effects are likely to be important in the functional role of the MOC system. Experimental results suggesting roles for the MOC system in dynamic range control, anti-masking and protection implicitly assume that the system functions for ongoing sounds, because of long latencies for responses and long lag times for peripheral effects. This assumption is consistent with the present results, demonstrating that there is minimal response adaptation for sounds of duration as long as 10 s. Whatever the precise role of the MOC system, sound-evoked MOC effects are expected to be stable for long-duration sounds.
We thank M. L. Duca for technical assistance and Drs. John Guinan, Jr., M. Charles Liberman, and Ronald K. de Venecia for comments on an earlier version of the manuscript.

This work was supported by National Institute on Deafness and Other Communication Disorders Grant DC-01089.

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