Behavioral Studies of the Olivocochlear Efferent System

Learning to Listen in Noise

Bradford J. May, PhD; Jennifer Budelis; John K. Niparko, MD

Background: Olivocochlear (OC) neurons make up an efferent, descending auditory system that returns sound representations to the inner ear soon after they have entered the brain. Efferent inputs into the cochlea modulate outer hair cell activity to improve the neural encoding of auditory signals in background noise. Based on this physiological evidence, loss of efferent feedback is expected to degrade perception in noise. Attempts to confirm this prediction with long-term audiological assessments have met with mixed results.

Objective: To isolate procedural factors that may diminish the demonstration of long-term OC deficits in listening tasks.

Design: Operant conditioning procedures were used to train domestic cats to signal a change in the location of an auditory stimulus by responding on a lever. The smallest detectable change in location was measured by manipulating the distance between speakers under quiet conditions and in the presence of background noise. Functional consequences of efferent feedback were evaluated by comparing the sound localization thresholds of OC-lesioned cats with normal controls.

Results: As predicted by the hypothesized function of OC feedback systems, the lesioned cats exhibited significantly elevated thresholds only when tested in background noise. This initially poor performance returned to normal values after long-term exposure to the testing procedure.

Conclusions: The results of our animal studies support the OC enhancement of sound localization behavior in background noise. Also, our behavioral observations suggest the acquisition of alternate listening strategies that allowed lesioned cats to minimize the functional consequences of their auditory deficits by attending more closely to remaining directional cues. These learned compensatory behaviors were encouraged by our present experimental design, which incorporated long-term training under consistent stimulus conditions. These findings point out the potential limitations of the highly routine audiological procedures that have been used to assess the impact of OC feedback on human hearing.

Arch Otolaryngol Head Neck Surg. 2004;130:660-664

The peripheral auditory system distributes the physical dimensions of an acoustic stimulus across large populations of neurons. The extraction of elemental perceptual attributes, such as loudness, pitch, and location, from this highly encoded representation demands intensive neural computations that involve no less than 9 subcortical nuclei. Information does not simply ascend the processing levels of the central auditory system. Within each nucleus, ascending representations are transformed by descending influences from higher-order neurons to emphasize the specific parameters that characterize a sound.

The most widely studied efferent auditory pathway is the olivocochlear (OC) system, which links the superior olivary complex to the cochlea. These efferent projections constitute a reflex arc that has the capacity to modify the neural representations of sound at the earliest stages of auditory processing (Figure 1A). Although 2 separate OC systems are implied by anatomical differences between efferent neurons in the medial and lateral brainstem, the current physiological descriptions are limited to medial OC (MOC) neurons. The present study investigated the behavioral consequences of MOC influences that are inferred from these physiological results.

Olivocochlear projections terminate within the cochlear nucleus and inner ear (Figure 1B). The MOC fibers influence cochlear sensitivity and frequency tuning by altering the sound-driven elec-
tromotile responses of outer hair cells. This mechanism for automatic gain control may protect the ear from damaging sounds and also enhance hearing in background noise. Because outer hair cells play a pivotal role in MOC feedback, common forms of sensorineural hearing loss compromise not only ascending auditory representations but also the principal effectors of the descending OC system.

It is possible to manipulate OC neurons independently of the ascending auditory pathways because efferent axons follow a separate course through the brainstem and into the cochlea. In most animal studies, the OC fibers are exposed along the floor of the fourth ventricle (Figure 2A), where the neurons may be activated by electrical stimulation or silenced by surgical lesions. These interventions most effectively address the extensively crossed pathway of the MOC system.

On exiting the lateral brainstem, OC axons enter the cochlea via the inferior branch of the vestibular nerve. This anatomical detail has important clinical implications. When the vestibular nerve is sectioned to alleviate intractable balance disorders, patients maintain efferent function but lose all efferent feedback to the affected ear (Figure 2B).

Previous clinical studies have attempted to associate OC lesions with a unique pattern of hearing loss. These audiological assessments have investigated tone detection, intensity and frequency discrimination, loudness adaptation, frequency selectivity, and spatial lateralization. Although an emphasis has been placed on stimulus conditions that maximize OC influences in physiological preparations, demonstrations of auditory deficits in patient populations have been equivocal.

Based on clinical outcomes, it was hypothesized that conventional audiological procedures may fail to assess OC function. To test this hypothesis, an animal behavior study was conducted to evaluate the effects of bilateral OC lesions on the sound localization behaviors of domestic cats. As predicted by previous behavioral and physiological results, lesioned cats showed poor performance when directional acuity was measured in the presence of continuous background noise. Initially robust perceptual deficits diminished after repeated testing under constant stimulus conditions. These findings suggest that low-uncertainty audiological procedures may obscure the functional significance of efferent feedback by promoting compensatory listening strategies.

### METHODS

All surgical and behavioral procedures were approved by the Institutional Animal Care and Use Committee of The Johns Hopkins School of Medicine, Baltimore, Md. Detailed descriptions of training methods for sound localization testing in cats are provided in previous publications.

Experiments were performed on 6 adult male cats. The cats were individually caged and fed a restricted diet of dry chow. The feeding regimen was supplemented by liquefied meat paste that served as rewards for correct responses during behavioral testing sessions. Cats showed a strong appetite for meat paste and only moderate food deprivation was needed to motivate subjects to work continuously for hourly sessions. Each cat maintained clean ears, good general health, and normal adult weights for the course of experiments.

Experimental trials were designed to test the subject's ability to detect changes in the elevation of a sound source in quiet and in background noise. The cats were trained to release a response lever when auditory stimuli shifted from a reference speaker directly in front of the subject (0° elevation) to a randomly selected comparison speaker at a higher elevation in the median plane. After correct releases, a peristaltic

---

Figure 1. The reflex arc of medial olivocochlear neurons. A, The auditory brainstem of the cat in frontal section. Sound representations from the ear ascend to the olivary complex via the ventral afferent pathway and project back to the ear via the dorsal efferent pathway. B, Cross-sectional view of the inner ear. The major ascending afferent pathway arises from inner hair cells. Descending olivocochlear projections terminate on outer hair cells. Adapted from Hearing Research (Liberman MC. Effects of chronic cochlear de-differentiation on auditory-nerve response. Hear Res. 1990;49:209-224) ©1990, with permission from Elsevier.

Figure 2. Functional manipulations of the olivocochlear pathways. A, Most laboratory studies involve electrical stimulation or surgical lesions along the floor of the fourth ventricle. Brainstem lesions are most effective if they are made bilaterally. B, Vestibular nerve (VN) lesions eliminate olivocochlear projections in route to the ear. AN, auditory nerve; CBL, cerebellum; CN, cochlear nucleus; IC, inferior colliculus; LSO, lateral superior olive; MSO, medial superior olive; SC, superior colliculus. Adapted from Hearing Research (Liberman MC. Effects of chronic cochlear de-differentiation on auditory-nerve response. Hear Res. 1990;49:209-224) ©1990, with permission from Elsevier.
pump delivered 1 mL of liquefied food to a spout near the subject’s mouth.

Auditory stimuli were noise bursts with a duration of 200 milliseconds and rise and fall times of 10 milliseconds. The noise bursts were synthesized for each presentation using a digital-to-analog converter with a sampling rate of 100 kHz (RP2; Tucker Davis Technologies, Alachua, Fla). Noise spectrum levels were randomized from 5- to 15-dB sound pressure level (SPL) to eliminate loudness cues that may have coincided with speaker changes.

Sound localization thresholds were derived from responses to an array of comparison speakers in the median plane. The comparison speaker nearest the reference speaker yielded low detection rates. The most widely spaced speaker elicited near-perfect performance. No change from the reference to a comparison speaker occurred on 20% of the trials to monitor false-positive responses (ie, guessing). On average, less than 20% of these so-called catch trials elicited false alarms.

Threshold was defined as the change in location where response rates reached the signal detection convention \( d' = 1 \). Signal detection methods provide an unbiased estimate of threshold by correcting for false alarm rates. This statistic was calculated as follows: \( d' = z(P_{hit}) - z(P_{false alarm}) \), where \( z(P_{hit}) \) is the \( z \) score for the percentage of hits for a comparison speaker and \( z(P_{false alarm}) \) is the \( z \) score for the percentage of false alarms for catch trials. Because \( d' \) usually does not equal 1 at any of the comparison speaker locations, the change in elevation at threshold was interpolated from measured values.

Reported thresholds were based on combined psychophysical data from a minimum of 10 consecutive testing sessions. To contribute to this summary, daily thresholds could not deviate by more than 20% from average values or show general trends toward improving (or deteriorating) performance. Also, false alarm rates could not exceed 30% on any day. Trained cats rarely failed to meet the criteria for stability.

Testing in noise began after subjects demonstrated stable detection of target stimuli under quiet conditions. Continuous broadband noise was presented from a fixed location directly over the subject’s head. The level of the background noise was gradually increased over several sessions to determine the maximum tolerable level for subjects with intact OC systems. A noise spectrum level of 15-dB SPL proved to be challenging enough to elevate sound localization thresholds without disrupting behavioral stability.

Olivocochlear influences on sound localization behavior were investigated by making brainstem lesions in 3 cats. The objective of the lesion was to transect OC axons as they pass beneath the floor of the fourth ventricle (Figure 2A). This route is taken by all crossed fibers as well as by a substantial number of uncrossed MOC fibers. The largely uncrossed lateral OC pathway is spared by this lesioning paradigm. After the cerebellum was elevated to gain access to the fourth ventricle, bilateral incisions were placed in relation to anatomical landmarks provided by the anterior and posterior cerebellar peduncles. The cuts were oriented in the parasagittal plane at opposite sides of the midline (Figure 2A).

Domestic cats have the acute auditory sense of a nocturnal predator. In addition to their remarkably sensitive hearing, these animals have excellent spatial acuity. Sound localization thresholds thus serve as a practical yet stringent test of optimal auditory performance.

The 3 intact cats produced thresholds that averaged less than 4° under quiet conditions (Figure 3A). Thresholds increased to 6.7° in continuous background noise (Figure 3B). Although noise effects were significant (paired \( t \) test, \( P<.05 \)), this outcome was predetermined because standard testing conditions were ascertained by increasing noise levels until localization deficits were observed in intact cats.

Olivocochlear lesions exacerbated the disruptive effects of background noise on sound localization behavior. Average thresholds of the 3 lesioned cats more than doubled in relation to normal baselines (Figure 3D). The statistical difference between lesioned and intact cats was highly significant (paired \( t \) test, \( P<.005 \)). Despite their pronounced noise deficits, the lesioned cats maintained excellent directional hearing under quiet conditions (Figure 3C).

The magnitude of sound localization deficits decreased in lesioned cats with prolonged testing. Auditory compensation is illustrated by the daily postlesion thresholds of cat Ba3 (Figure 4). The localization behaviors of this representative subject appeared normal under quiet testing conditions. After a stable threshold was obtained in quiet, noise levels were gradually increased to standard noise conditions (15-dB SPL). Unlike the intact cats, who adapted quickly to background noise, the lesioned cats required several weeks of additional training, smaller incremental changes, and more repetitive exposures to complete the process of adjustment. Thresholds in Figure 3C and D reflect the first 10 days of stable performance in quiet and standard noise conditions for each subject. Cat Ba3 produced stable thresholds in background noise for weeks before developing compensatory listen-
The present experiments used behavior-based audiological procedures to assess the effects of OC lesions on sound localization performance under optimum (quiet) and challenged (noise) conditions. Intact cats showed excellent spatial acuity in quiet. Normal levels of performance were also noted in subjects with bilateral OC lesions. Based on these observations, it may be assumed that generalized hearing disorders or motor deficits did not impair the ability of lesioned cats to perform the localization task. Also, these results suggest a limited role for OC feedback under quiet listening conditions.

The relatively small effects of continuous background noise on the sound localization thresholds of intact cats support previous interpretations for the OC enhancement of auditory processing in noise. The deficits of cat Sa6 may reflect exceptional natural variations that have been described for the strength of OC feedback in humans and other animals. Clinical studies have investigated this phenomenon by measuring the suppression of otoacoustic emissions by the activity of OC neurons. Weak efferent suppression is correlated with poor performance in background noise.

Lesioned cats exhibited significantly larger localization deficits than noise controls. These findings support correlation studies in humans but do not replicate the modest or inconsistent perceptual deficits that are induced by surgical procedures in patients who have undergone a vestibular neuroectomy. Although the clinical studies may be criticized because vestibular nerve sections are often associated with Ménière’s disease, lesioning paradigms also yield contradictory results in animals with normal preoperative hearing.

The OC lesion was designed to evaluate the function of recurrent connections between the brain and cochlea that are thought to preserve the neural encoding of auditory information in the presence of background noise. Loss of the OC efferent pathway did not produce the expected, consistent loss of sound localization behavior. Rather, considerable variability was observed between subjects during long-term audiological assessments. Patterns of response that slowly returned to normal baseline levels of performance suggest learned compensation in some subjects. Indeed, experimental protocols with prolonged testing tend to report less robust effects of OC efferent pathway lesioning in contrast to short-term assessments, even when similar testing procedures are used. This apparent recovery of function is not a consequence of incomplete surgical procedures. Genetically modified mice with no peripheral OC function also achieve normal auditory performance in background noise with sufficient training.

It is tempting to consider the long-term functional consequences of OC lesions in terms of central auditory reorganization following peripheral sensory defects. In cats with restricted cochlear lesions, the frequency selectivity of the deprived cortical region expands to include intact adjacent frequencies. Injury- and use-related cortical reorganizations appear analogous; ie, expanded cortical representations have been linked to superior performance in operant-conditioned discrimination tasks that require frequency specific behavioral response. Although the details of the neural reorganizations that subserve improved signal detection in noise remain to be described, the present data suggest that the recovery of auditory signal processing after loss of efferent feedback is amenable to similar training effects.

Our observations in cats with experimentally induced hearing deficits provide a simple, but informative, model for future studies of the complex dynamics between auditory experience and aural rehabilitation. From this perspective, learning effects that enhance auditory discrimination in OC-lesioned cats represent an important step toward the refinement of procedures to promote the acquisition of communication skills after hearing is restored by cochlear implantation or conventional aids. The question remains, “Do training strategies that succeed within the narrow confines of routine audiological procedures prepare hearing-impaired listeners for less predictable auditory challenges?” To answer this question, descriptions of functional recovery must extend beyond controlled laboratory conditions to the complex and uncertain environments that characterize everyday listening.

Submitted for publication January 6, 2004; accepted January 21, 2004.

This research was funded by grant R01 DC00954 from the National Institute on Deafness and Other Communication Disorders, Bethesda, Md.

This study was presented at the Ninth Symposium on Cochlear Implants in Children; April 25, 2003; Washington, DC.

Corresponding author and reprints: Bradford J. May, PhD, The Johns Hopkins University, Department of Otolaryngology–Head and Neck Surgery, Traylor Bldg, Room 505, 720 Rutland Ave, Baltimore, MD 21205 (e-mail: bmay@jhu.edu).
REFERENCES