Superior Canal Dehiscence
Mechanisms of Pressure Sensitivity in a Chinchilla Model
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Background: Patients with superior canal dehiscence syndrome may experience vertigo and nystagmus when pressure changes occur in the external auditory canal, the middle ear, or the intracranial space. The cause is a defect in the bone of the superior canal.

Objective: To study the mechanisms of pressure sensitivity of the labyrinth in superior canal dehiscence syndrome and its surgical repair in a chinchilla model.

Methods: We investigated the changes in firing rates of vestibular nerve afferents in the chinchilla in response to changes in external auditory canal pressure before and after fenestration of the superior canal, and after repair of the fenestra.

Results: Before superior canal fenestration, external auditory canal pressure changes caused no responses in horizontal canal or otolith afferents, and only 1 of 9 superior canal afferents responded to pressure. After fenestration, all superior canal afferents were excited by positive pressure and inhibited by negative pressure. Half of 18 otolith and most (21 of 33) horizontal canal afferents were unaffected by pressure. The superior canal afferents had higher pressure gain than the horizontal canal afferents (P = .03). Pressure responses could be abolished only by applying a rigid seal to the fenestra.

Conclusions: Fenestration of the superior canal rendered all superior canal afferents sensitive to pressure, whereas less than half of the other afferents became pressure sensitive. The direction of the superior canal afferent responses agreed with the predictions of our model of endolymph flow within the superior canal. A rigid seal applied to the fenestra abolished pressure sensitivity while maintaining physiologic rotational sensitivity.


THE VESTIBULAR labyrinth can become sound (Tullio phenomenon) or pressure (Hennebert sign) sensitive in pathological states affecting the integrity of the labyrinthine bone.1,2 Recently, Minor and colleagues3 identified the superior canal dehiscence syndrome, in which the bone overlying the superior semicircular canal is deficient. Carey and colleagues4 described histological correlates of the syndrome in a temporal bone survey. The dehiscence creates an additional third mobile window in the labyrinth, which may cause episodic vertigo and nystagmus in response to intense sound or changes in external ear canal, intracranial, or middle ear pressure.5

The axis of evoked nystagmus in the superior canal dehiscence syndrome aligns with the plane of the affected superior canal, indicating that the response originates mainly from that canal.6,7 Accordingly, Yagi et al8 found that patients with a labyrinthine fistula in a single semicircular canal showed compensatory eye movements within the plane of that canal. Cremer et al9 studied a patient with a postoperative fistula in the posterior semicircular canal, and found that pressure changes in the external ear canal induced nystagmus in the plane of the affected posterior canal.

The proposed mechanism for the nystagmus evoked by pressure changes in the external auditory canal in patients with superior canal dehiscence syndrome is motion of the ampulla of the superior canal related to the increased compliance of the endolymphatic system created by the dehiscence. In this hypothesis (Figure 1), positive pressure in the external ear canal would move the tympanic membrane and stapes inward. Normally, outward movement of the round window membrane would relieve the resulting pressure gradient. The presence of a third mobile window allows the membranous canal to bulge upward through the overlying defect in the bone. The flow of endolymph...
SUBJECTS AND METHODS

SUBJECTS AND AFFERENT RECORDINGS

Institutional guidelines of The Johns Hopkins University School of Medicine, Baltimore, Md, regarding animal experimentation were followed. Nine adult chinchillas of either sex were anesthetized with intraperitoneal 5.5-diallylbarbituric acid (Dial; Sigma Chemical Co, St Louis, Mo), 40 mg/kg. A tracheotomy was performed to maintain a patent airway, and animals were kept at a core body temperature with a servocontrolled heating pad (model 40-90-8B; Frederick Haer & Company, Bowdoinham, Me). After placement in a stereotactic holder, the superior bulla was opened. The extracranial facial and superior vestibular nerves were identified, and the bone overlying the eighth nerve was removed. Extracellular afferent potentials were recorded with glass microelectrodes (model M1B100F-4; World Precision Instruments, Inc, Sarasota, Fla) filled with 3N sodium chloride and with impedances of 10 to 30 MΩ. Microelectrodes were mounted on a 3-dimensional microdrive (model MO-22; Narishige Scientific Instrument Lab, Tokyo, Japan) and directed into the eighth nerve. Extraneuronal activity was amplified 500 to 5000 times (model 2400A; Dagan Corporation, Minneapolis, Minn), bandpass filtered from 100 Hz to 3 kHz, digitized at 5 kHz, and stored. The stereotactic apparatus was mounted on a gimbaled structure that allowed any of the semicircular canals to be tilted into the earth-horizontal plane for rotational testing. The structure was mounted on a servocontrolled rate table (model 130-80/ACT2000; Acutronic USA, Inc, Pittsburgh, Pa) programmed to provide various earth-horizontal rotations.

Once an afferent was isolated, each unit was sampled for 10 to 20 seconds at rest before stimulation. Then the structure was tilted to determine if the afferent was tilted sensitive, ie, an otolith afferent, and rotated in the various canal planes to determine if it was a canal afferent, and, if so, which canal it innervated. Normalized coefficients of variation (CVs) were computed to classify afferents as regular (CV<0.1), intermediate (0.1<CV<0.2), or irregular (CV>0.2). The pressure sensitivity was calculated from neuronal responses measured in spikes per second (sp·s⁻¹) with regard to pressure change, measured in millimeters of mercury (mm Hg). The rotational sensitivity was measured as change in firing rate in spikes per second per rotational velocity in degrees per second (deg·s⁻¹).

FENESTRATION OF THE SUPERIOR CANAL

A 0.3-mm fenestra was made with a footplate perforator at the uppermost portion of the superior canal, where it protruded into the mastoid bulla. After recording afferent responses with the fenestra open, it was covered with muscle alone or in combination with a rigid layer of cyanoacrylate, and the stimuli were repeated.

PRESSURE STIMULATION

Pressure stimuli were generated by an elastic bulb or an air-filled syringe attached via inelastic tubing to the sealed external ear canal. Pressure was monitored in centimeters of water based on fluctuations of the fluid column in an attached burette in 5 animals or by a digital pressure transducer (model 60-3002; Harvard Apparatus, Inc, Holliston, Mass) in another 4. Couplings between the tubing and the hollow ear bar and between the ear bar and the external ear canal were sealed with vacuum grease to maintain pressure gradients. The stimuli used were sinusoidal or pulsatile negative or positive pressure changes in the external ear canal (mean absolute change, 13 mm Hg; range, −50 to 60 mm Hg).
RESULTS

Pressure responses were recorded from 20 afferents before the fenestration and from 60 afferents after the fenestration. During the measurements, physiologic responses of the afferents to linear or angular acceleration remained intact despite fenestration or the repair technique.

BEFORE FENESTRATION

Responses to pressure stimuli were rare before superior canal fenestration. Only 1 of 9 superior canal afferents modified its firing rate in response to pressure stimuli. Two of 9 superior canal afferents showed delayed responses, in which the firing rate decreased continuously after a few seconds of delay during prolonged stimulation, and then recovered slowly to the baseline. The remaining 6 superior canal, 5 horizontal canal, and 6 otolith afferents did not respond to pressure stimuli before the fenestration.

AFTER FENESTRATION

Changes in the afferent discharge rate during sinusoidal or pulsatile pressure stimuli were prominent after fenestration (Figure 2 and Figure 3). Each of the 9 superior canal afferents responded to pressure changes after fenestration. Pressure-induced responses were noted in 12 (36%) of the 33 horizontal canal afferents and in 9 (50%) of the 18 otolith afferents following fenestration. Responses to positive pressure were excitatory, and responses to negative pressure were inhibitory.

Pressure sensitivity, defined as the change in firing rate divided by the change in pressure, was higher for superior canal than for horizontal canal afferents (mean±SD, 2.8±1.9 sp·s⁻¹·mm Hg⁻¹ [n=8] vs 1.3±1.0 sp·s⁻¹·mm Hg⁻¹ [n=5]; P=.03, 1-tailed t test). The mean response was larger for negative pressure than for positive pressure in regular and intermediate afferents (mean±SD, 1.8±1.3 vs 0.8±0.7 sp·s⁻¹·mm Hg⁻¹; P=.005, 1-tailed t test). For 2 irregular afferents (1 superior canal and 1 otolith afferent), pressure sensitivities could not be compared because of cutoff of the response during negative pressure. For only one afferent, an irregularly discharging otolith afferent, the positive and negative stimuli were excitatory.

Pressure responses varied according to afferent discharge regularity. After the fenestration, 16 (48%) of the 33 regular, 3 (60%) of the 5 intermediate, and 11 (61%) of the 18 irregular afferents responded to pressure changes. The magnitude of the pressure sensitivity correlated (r=0.55, P=.03, 1-way analysis of variance) with an increase in the CV.

AFTER THE REPAIR OF THE FENESTRA

A loose seal over the fenestra made with muscle placed over the dehiscence led to a reduction in the pressure responses in 1 superior canal afferent, but it did not have a significant effect in 3 other afferents. In contrast, a rigid seal over the fenestra, established by applying cyanoacrylate to the muscle and allowing it to cure, abolished the pathological pressure effects (Figure 4). In 3 of these 4 afferents, it was possible to extract the rigid seal while still recording from the afferent. Responses of these afferents to pressure after removal of the seal were similar to those recorded before the repair of the fenestra. The responses to 1-Hz rotations were unchanged after application of the seal to the fenestra compared with before application in the 2 afferents that were tested. For the superior canal afferent, the rotational sensitivity was 0.16 sp·s⁻¹/deg·s⁻¹ before and after the seal was applied. For the horizontal canal afferent, the rotational sensitivity was

Figure 1. Hypothesis for the mechanism of the superior canal dehiscence syndrome. A dehiscent bone in the superior canal acts as a third mobile window in the labyrinth. Positive pressure (arrows) moves the tympanic membrane and ossicular chain inward and causes utriculofugal endolymph flow in the superior canal. This causes excitation of the superior canal afferents.

Figure 2. The external auditory canal (EAC) pressure, the firing rate, and the nerve potential were recorded for a horizontal canal afferent during sinusoidal pressure stimuli after the fenestration of the superior canal.
We studied the responses of vestibular nerve afferents to pressure changes applied in the external auditory canal of chinchillas before and after fenestration of the superior canal. The strongest and most frequent responses were found in superior canal afferents, which all responded to pressure stimulation after the fenestration. Positive pressure in the external ear canal uniformly caused excitation in superior canal afferents, which agrees with our model of utriculofugal endolymph movement in the superior canal. Accordingly, negative pressure caused inhibition, consistent with utriculopetal flow of endolymph within the superior canal.

After the fenestration, some horizontal canal afferents also modified their firing rates in response to pressure stimuli, although the change in firing rate induced by a comparable pressure stimulus was greater for superior than for horizontal canal afferents. The direction of the pressure stimulus and the response of the afferent were the same for horizontal as for superior canal afferents: positive pressure resulted in excitation, and negative pressure resulted in inhibition. There are at least 2 possible mechanisms for these pressure-induced responses in horizontal canal afferents after fenestration. First, the increased compliance in the membranous labyrinth established by the dehiscence may have resulted in ampullopetal deflection of the horizontal canal ampulla in response to positive pressure and in ampullofugal deflection in response to negative pressure. Alternatively, dilational pressure might act across the ampulla of the horizontal canal in the presence of the fistula in the superior canal. Afferent responses due to dilational pressure have been shown to occur in toadfish for horizontal canal and utricular afferents.12 Rabbitt et al12 suggest that dilational pressure may be as important as endolymph flow in the macromechanical function of the semicircular canal. However, dilational

**Figure 3.** Changes in the external auditory canal (EAC) pressure and the firing rate of a superior canal afferent in response to negative (A) and positive (B) pressure pulses after fenestration of the canal.

**Figure 4.** A superior canal afferent responding to sinusoidal external auditory canal (EAC) pressure while the superior canal fenestra is open (A) or sealed with muscle and a rigid layer of cyanoacrylate (B).
pressure sensitivity presents a problem for terrestrial vertebrates, in whom atmospheric pressure changes could be rapidly conveyed to the perilymph compartment via the tympanic membrane and ossicular chain. If gradients in pressure were created between endolymph and perilymph, the ampulla would dilate or contract, modulating canal afferent firing. Presumably, the bony semicircular canal functions to create a closed system in which pressure is equalized between endolymph and perilymph. The presence of a fenestra, even remote from the horizontal canal, could, therefore, produce afferent responses to changes in the external auditory canal pressure.

After fenestration of the superior canal, the inhibitory responses caused by negative pressure were generally larger than the excitatory responses evoked by positive pressure. The direction of responses in other types of vestibular afferents was similar; only 1 of 18 otolith afferents was excited by both stimuli. Several clinical reports have also found that negative pressure in the external ear canal stimulates the labyrinth more than positive pressure. Physiologically, the excitatory response to acceleration in vestibular afferents is larger than the inhibitory response. There are at least 2 potential reasons for the difference in the magnitude of the excitatory and inhibitory responses to pressure and rotational stimuli. First, negative external ear canal pressure in our experimental preparation could be more reliably maintained than could positive pressure. Negative pressures tended to coapt the soft tissues and vacuum grease and maintain the sealed space of the external ear canal, whereas positive pressures tended to push open these interfaces. Second, tympanic membrane displacement to equal pressure stimuli has also been shown to be significantly larger for outward (caused by negative pressure) than for inward (caused by positive pressure) motion. This asymmetry may be further reinforced in the level of malleus movement.

Wall and Casselbrant studied perilymphatic fistulas in a chinchilla model. They found eye movement responses in 9 (69%) of 13 ears with an experimental fistula in the bony labyrinth, using external ear canal pressure levels of ±250 mm H2O. They observed horizontal and vertical eye movements, but they did not emphasize if the site of the fistula and the eye movements recorded were correlated. The present study shows that afferents innervating the superior canal are most sensitive to pressure stimuli after fenestration of that canal. This is consistent with our clinical finding that the plane of the eye movements of patients with superior canal dehiscence syndrome aligns with that of the affected canal.

Before fenestration, only 1 of the 20 afferents that were tested with pressure stimuli showed a change in firing rate during the application of pressure. In contrast, 30 of the 60 afferents recorded after fenestration had a pressure-induced response. Irregularly discharging afferents were more sensitive to these pressure stimuli than were regularly discharging afferents. The findings are consistent with the notion that the dehiscence creates a third mobile window into the labyrinth, rendering it more sensitive to pressure stimuli.

Irregularly discharging afferents were more sensitive to pressure than were regularly discharging afferents. A similar difference in sensitivity to rotation is noted for high-gain irregularly discharging afferents compared with regularly discharging afferents. The proportion of units sensitive to pressure was also highest in the group of irregular afferents.

The fenestra made in the superior canal in our experiments was 0.3 mm in diameter and was open to air, whereas the diameter of dehiscence in patients with superior canal dehiscence syndrome is several millimeters and opens into the middle cranial fossa. Most afferents in our study modulated their firing rate after fenestration, with external ear canal pressure changes of only a few millimeters of mercury. These pressure levels correspond to those delivered through a pneumatic otoscope during the clinical fistula test, but a direct comparison with pressure levels applied through Valasalva maneuvers is difficult. Thus, the level of critical pressure producing clinical symptoms and signs in patients with superior canal dehiscence syndrome remains to be studied.

An ideal repair of a canal dehiscence would close the defect so as to eliminate these pathologic responses, but maintain the patency of the lumen of the canal, allowing physiologic endolymph flow and the transduction of information about head movements. We attempted such a repair by sealing the fenestra with muscle without obliterating the lumen of the canal. Sealing with soft tissue alone failed to abolish pressure responses. Instead, rigid repair of the superior canal fenestra abolished pathologic vestibular afferent responses to pressure, but still preserved physiologic responses to head rotation. Thus, a rigid seal appears to be important for immediate elimination of the pressure sensitivity of the labyrinth in patients with superior canal dehiscence syndrome. This has important implications for surgeons planning to repair a dehiscent canal. A rigid closure, as might be achieved with bone or bone cement, would seem to be required for elimination of symptoms. The availability of calcium phosphate bone cements to close such defects is appealing, but the potential ototoxicity of such materials in contact with perilymph has not been determined. It is also possible that soft tissue repair alone would eventually lead to scarring and rigidity of the seal. Therefore, a further evaluation of these 2 techniques will need to consider the long-term effects of each.

The findings in our animal model confirm that the pressure responses in superior canal dehiscence syndrome originate mainly from superior canal afferents. Fenestration of the superior canal rendered all superior canal afferents sensitive to pressure, whereas less than half of the other afferents became pressure sensitive. The direction of the superior canal afferent responses agrees with our model of endolymph flow within the superior canal. The surgical repair of superior canal dehiscence syndrome should aim to rigidly seal the superior canal defect, which immediately abolished the pressure sensitivity.
while maintaining the physiologic rotational sensitivity in our experimental model.

Accepted for publication July 11, 2001.

This study was supported by research grants from the Finnish Academy (grant 48029), the Finnish Medical Association, and the Finnish Research Foundation of Otolaryngology, Helsinki, Finland (Dr Hirvonen); grant R01 DC02390 from the National Institute of Deafness and Other Communication Disorders, Bethesda, Md; and the American Hearing Research Foundation, Chicago, Ill.

Presented as a poster at the 22nd Midwinter Meeting of the Association for Research in Otolaryngology, St Petersburg, Fla, February 7, 2001.

We thank Brian Dunham, MD, for preparing Figure 1.

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