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Stress Electrocochleography

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Abstract: Electrocochleographic recordings after changes of middle-ear and intracranial pressure were studied in a group of otologically normal subjects and in patients with suspected Ménière's disease. Electrocochleography performed under these conditions was called *stress electrocochleography*. It was useful to distinguish among Ménière's disease, benign positional vertigo, and a round-window fistula. Changes of middle-ear pressure, whether positive or negative, always resulted in a rise of the SP/AP ratio. Raised intracranial pressure after Trendelenburg positioning showed fluctuations of the SP/AP ratio in both normal subjects and symptomatic patients. However, in normal subjects, a congruent pattern of these fluctuations was apparent, whereas symptomatic patients exhibited a discordant pattern. The discordant pattern, typical for Ménière's disease, showed an increase of the SP voltage, whereas the AP voltage decreased. In benign positional vertigo, the SP voltage decreased, and the AP voltage increased, once during Trendelenburg positioning and again at the end of the test when starting position was resumed. During raised intracranial pressure after the Queckenstedt maneuver, round-window fistulas showed an increase of the SP voltage, whereas the AP voltage decreased considerably. At our clinic, stress electrocochleography has become an important neurotological test in the differential diagnosis of Ménière's disease.

Keywords: benign positional vertigo; cervicogenic otoocular syndrome; electrocochleography; electrovestibulography; intracranial pressure; Ménière's disease; middle-ear pressure; perilymphatic fistula; Queckenstedt; stress electrocochleography; Trendelenburg

Electrocochleography has become a standard neurootological test for the diagnosis of Ménière's disease. Clinical experience, however, shows that such conditions as benign positional vertigo and perilymphatic fistula can present with similar symptoms. Distinguishing between these conditions can be difficult when Electrocochleographic findings are consistent with endolymphatic hydrops, suggesting Ménière's disease.

Learning from the cervicogenic otoocular syndrome (COO), which responds invariably to the insertion of a ventilation tube, a procedure that results in the return of the SP/AP ratio to normal levels, we have become aware that the inner ear can have an exaggerated sensitivity to minor pressure changes [1; see also Franz et al., "The Cervicogenic Otoocular Syndrome," this issue]. This exaggerated sensitivity to pressure changes is observed also in patients with Ménière's disease, although the response to the insertion of a ventilation tube drops to 67% (Table 1). This altered response would suggest that various conditions of the inner ear could express various forms of pressure sensitivity.

Over the last 12 months, we have focused on the inner ear's response to pressure. Patients were submitted to changes of middle-ear and intracranial pressure during which extratympanic electrocochleography was performed. We called this *stress electrocochleography*. Data from patients with suspected Ménière's disease was compared with findings from normal persons devoid of any ear disorder symptoms.

METHOD

Electrocochleography using click stimuli was performed with an extratympanic electrode placed on the eardrum and with conduction liquid in the tympanic recess. This arrangement has given an excellent morphological record of the tracings. A transtympanic electrode was used in those patients with a hearing loss and in those in whom clinical suspicion of an endolym-

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Table 1. Response of Ménière's Disease to Physiotherapy and Insertion of a Ventilation Tube as Compared with Pre-COO Syndrome and COO Syndrome

	Pre-COO Syndrome	COO Syndrome	Ménière's Disease
No. of patients	184	51	187
Treatment with ventilation tubes	2 (184)	43 (51)	46 (187)
Positive response to physiotherapy only	182	8 (15.7%)	—
Positive response to ventilation tube insertion	2 (2)	43 (43)	31 (46) (67.3%)

COO = cervicogenic otoocular.

phatic hydrops was not confirmed with an extratympanic electrode.

Increased middle-ear pressure was achieved through the Valsalva maneuver, and reduced middle-ear pressure was achieved through a modified Holmquist test using a Politzer bag. In the latter test, patients were asked to swallow with one nostril closed while the Politzer bag sucked air through the other nostril. Both procedures resulted in changes of middle-ear pressure ranging from +150 to +200 mm H_2O and −150 to −200 mm H_2O, respectively. The status of the middle ear was assessed with a Madsen impedance bridge. Once positive or negative pressure was created in the middle ear, patients were asked not to swallow, to prevent change to the pressure status of the middle ear.

Changes of middle-ear pressure seldom occurred in symptomatic patients, as they frequently presented with a mild eustachian tube dysfunction that prevented establishing negative or positive middle-ear pressure of a significant degree.

In all persons, intracranial pressure was raised through Trendelenburg positioning and the Queckenstedt maneuver. At least three consecutive recordings were obtained with patients in Trendelenburg position. In the Queckenstedt maneuver, intracranial pressure was raised by pulling the skin tight in front of the thyroid cartilages. This considerably reduced the venous blood return.

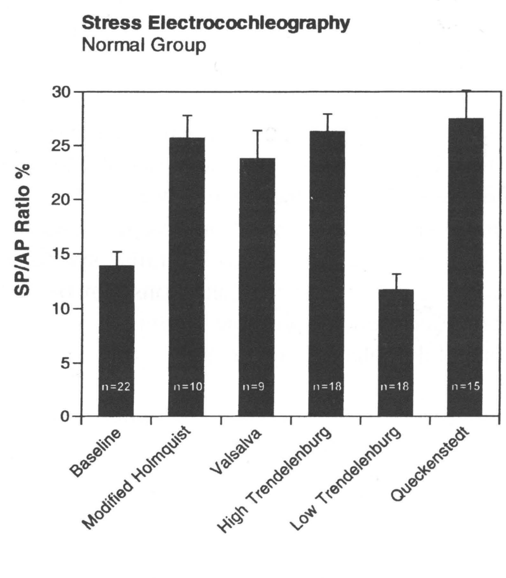
The baseline electrocochleography was performed with patients in the supine position and with the head raised slightly to 30 degrees. In Trendelenburg positioning, an angle not exceeding 20 degrees was permitted. The Trendelenburg positioning was performed within 1 second. This limitation was necessary to observe changes in the electrocochleogram that could be related to benign positional vertigo. For the Queckenstedt maneuver, patients were in the complete supine position.

For each group of patients, the mean SP/AP ratios were subjected to an arc-sine transformation before they were compared, using the Tukey-Kramer procedure for the multiple comparison of pairs of means of unequal sample size [2]. In each case, $\alpha = 0.05$.

RESULTS

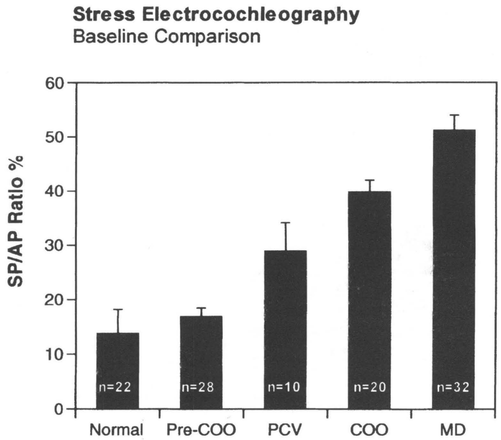
A summary of the results is shown graphically in Figures 1 through 5. Within the normal group (n = 22; mean age, 38.4 years; female-to-male ratio, 1:1) increase in middle-ear pressure (n = 10) as well as decrease in middle-ear pressure (n = 9) always resulted in an increase of the SP/AP ratio (see Fig. 1). The SP/AP ratio hardly exceeded 30%. The average SP/AP ratio was 25.7 ± 2.1% for negative middle-ear pressure and 23.8 ± 2.6% for positive middle-ear pressure. The ratio for negative middle-ear pressure was significantly different from that of the baseline electrocochleogram (13.9 ± 1.3%). On swallowing, the ratios returned to the baseline levels (Fig. 6).

Raised intracranial pressure after Trendelenburg positioning (n = 18) invariably resulted in fluctuations of the SP/AP ratio. The average fluctuations of the SP/AP ratio ranged from 26.3 ± 1.6% (high Trendelenburg maneuver) to 11.7 ± 1.4% (low Trendelenburg maneu-



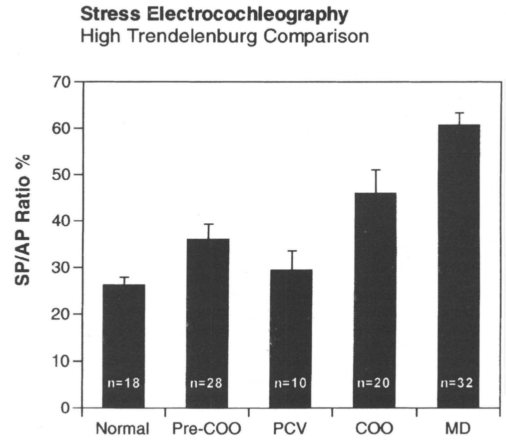
	Baseline	MH	Valsalva	High	Low
Baseline	-	-	-	-	-
MH	Sig	-	-	-	-
Valsalva	N/S	N/S	-	-	-
High	Sig	N/S	N/S	-	-
Low	N/S	Sig	N/S	Sig	-
Quec	Sig	N/S	N/S	N/S	Sig

Figure 1. Stress electrocochleography in normal subjects. Changes of negative middle-ear pressure are significant.



	Normal	Pre-COO	PCV	COO
Normal	-	-	-	-
Pre-	N/S	-	-	-
PCV	N/S	N/S	-	-
COO	Sig	Sig	Sig	-
MD	Sig	Sig	Sig	Sig

Figure 2. Stress electrocochleography, baseline comparison. The SP/AP ratio is raised significantly in COO syndrome and in Ménière's disease.

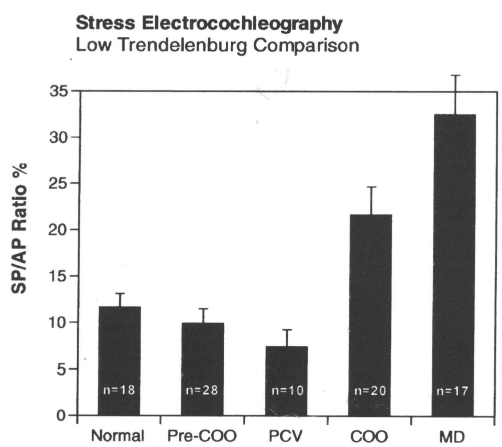


	Normal	Pre-COO	PCV	COO
Normal	-	-	-	-
Pre-	N/S	-	-	-
PCV	N/S	N/S	-	-
COO	Sig	N/S	N/S	-
MD	Sig	Sig	Sig	N/S

Figure 4. Stress electrocochleography, high Trendelenburg comparison. The SP/AP ratio is raised significantly in COO syndrome and in Ménière's disease.

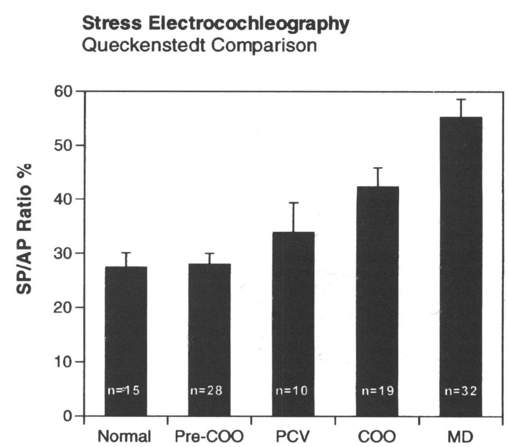
ver). The high Trendelenburg maneuver result was significantly different from the results from the baseline electrocochleogram (See Fig. 6).

Raised intracranial pressure after the Queckenstedt maneuver (n = 15) always showed a significant increase in the SP/AP ratio. The average SP/AP ratio was



	Normal	Pre-COO	PCV	COO
Normal	-	-	-	-
Pre-	N/S	-	-	-
PCV	N/S	N/S	-	-
COO	N/S	Sig	Sig	-
MD	Sig	Sig	Sig	N/S

Figure 3. Stress electrocochleography, low Trendelenburg comparison. The SP/AP ratio is raised significantly only in Ménière's disease.

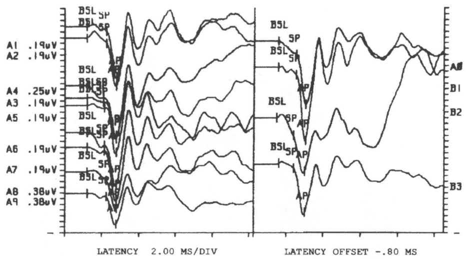


	Normal	Pre-COO	PCV	COO
Normal	-	-	-	-
Pre-	N/S	-	-	-
PCV	N/S	N/S	-	-
COO	N/S	Sig	N/S	-
MD	Sig	Sig	Sig	N/S

Figure 5. Stress electrocochleography, Queckenstedt comparison. The SP/AP ratio is raised significantly in Ménière's disease.

Stress Electrocochleography
Normal

Patient Robert **AGE** 30 **Date** 22-12-98



Interamplitudes (μV)

	SP	AP	SP BSL	AP	BSL	SP / AP
A1	-	-	+0.13	+1.66	Pre	0.08
A2	-	-	+0.15	+1.67	Pre	0.09
A3	↑	↑	+0.40	+1.78	Supine	0.22
A4	↓	↓	+0.17	+1.66	T-1	0.10
A5	↓	↓	+0.08	+1.56	T-2	0.05
A6	↑	↑	+0.40	+1.83	T-3	0.22
A7	↓	↓	+0.11	+1.79	Supine	0.06
A8	↑	↑	+0.55	+2.51	Q	0.22
A9	↓	↓	+0.21	+2.13	Post 30°	0.10
A0	↑	↑	+0.44	+2.15	MH	0.21
B1	↓	↓	+0.17	+1.64	Swallow	0.10
B2	↑	↑	+1.10	+3.49	Valsalva	0.31
B3	↓	↓	+0.19	+2.22	Swallow	0.09

Figure 6. Stress electrocochleogram from a normal subject demonstrating congruent changes of the SP and AP voltages during various middle-ear and intracranial pressure constellations.

27.5 ± 2.6%. The Queckenstedt maneuver result did not differ significantly from that of the high Trendelenburg maneuver, the modified Holmquist test, or the Valsalva maneuver, but it differed significantly from the low Trendelenburg maneuver result (see Fig. 1).

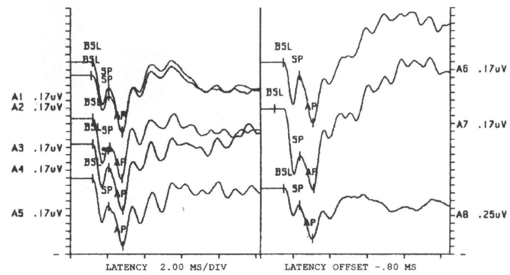
Changes of the SP/AP ratio during stress electrocochleography, and particularly in Trendelenburg positioning and in the Queckenstedt maneuver, always showed congruency in normal subjects: When the SP voltage increased, so did the AP voltage and vice versa (see Fig. 6).

Stress electrocochleography was performed without an attempt to change middle-ear pressure in 95 symptomatic patients with disorders as follows:

- Ménière's disease, 32; mean age, 56.6 years; female-to-male ratio, 1:2
- COO syndrome, 20; mean age, 48.5 years; female-to-male ratio, 4:3
- Pre–COO syndrome, 28; mean age, 45.6 years; female-to-male ratio, 4:1
- Benign positional vertigo, 12; mean age, 51.6 years; female-to-male ratio, 10:1

Stress Electrocochleography
Ménière's Disease

Patient S.A. **DOB** 12-05-37 **Date** 01-03-99



Interamplitudes (μV)

	SP	AP	SP BSL	AP	BSL	SP / AP
A1	-	-	+0.43	+1.23	Pre	0.35
A2	↑	↑	+0.54	+1.58	Pre	0.35
A3	↑	↓	+0.63	+1.34	T-1	0.47
A4	↓	↑	+0.49	+1.50	T-2	0.33
A5	↑	↑	+0.61	+1.52	T-3	0.40
A6	↓	↓	+0.26	+1.36	Supine	0.19
A7	↑	↑	+1.02	+1.78	Q	0.57
A8	↓	↓	+0.52	+1.67	Post 30°	0.31

Figure 7. Stress electrocochleogram in a patient with Ménière's disease. The discordant pattern of SP and AP voltages are also typical for COO syndrome and pre–COO syndrome.

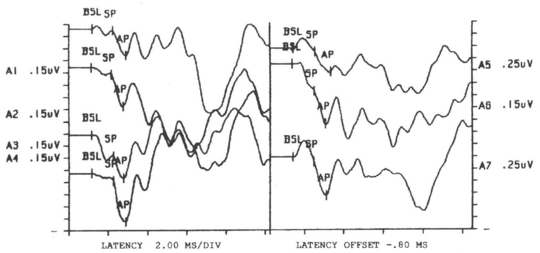
- Perilymphatic fistula in two female subject; ages, 56 and 45 years
- Suspected perilymphatic fistula in one male subject; age, 57 years

Baseline electrocochleograms showed a gradual increase of the SP/AP ratio within this group. Averaged ratios remained within 30% for the pre–COO syndrome and benign positional vertigo only. These ratios did not differ significantly from those of the baseline electrocochleograms of normal subjects. As expected, the SP/AP ratio increased significantly in the COO syndrome and the Ménière's disease. However, a concurrent significant difference was observed between the COO syndrome and the Ménière's disease (see Fig. 2).

Raised intracranial pressure after Trendelenburg positioning showed similarity to the normal subjects' fluctuations of the SP/AP ratio. In the pre–COO syndrome, the high Trendelenburg position averaged 36.0 ± 3.2%, and the low Trendelenburg position averaged 10.0 ± 1.5%. In benign positional vertigo, the averages for the high Trendelenburg maneuver were 29.5 ± 4.0% and for the low Trendelenburg position were 7.5 ± 1.8%. In the COO syndrome group, the high Trendelenburg position was averaged at 46.0 ± 5.0%, and the low Trendelenburg position was averaged at 21.7 ± 3.0%. The average high Trendelenburg position

Stress Electrocochleography
Posterior Canal Vertigo

Patient J.D. **DOB** 13-09-20 **Date** 20-04-99



Interamplitudes (μV)

	SP	AP	SP BSL	AP	BSL	SP / AP
A1	-	-	+0.02	+0.34	Pre	0.07
A2	↑	↑	+0.07	+0.48	T-1	0.15
A3	↑	↑	+0.26	+0.54	T-2	0.48
A4	⬇	⬆	+0.08	+0.60	T-3	0.14
A5	↓	↓	+0.05	+0.50	Supine	0.11
A6	↑	↑	+0.33	+0.75	Q	0.44
A7	⬇	⬆	+0.10	+0.83	Post 30°	0.12

Figure 8. Stress electrocochleogram in benign posterior canal vertigo. Typically, a discordant pattern of SP and AP voltages is present during Trendelenburg positioning an in resuming starting position, and with an increase of the AP voltage while the SP voltage decreases.

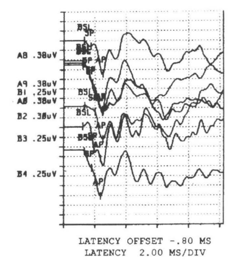
in Ménière's disease was 60.8 ± 2.5%, and the average low Trendelenburg position was 32.6 ± 4.2%. In this group, the ratios of the COO syndrome and Ménière's disease differed significantly from those of the normal group. The ratios of the pre–COO syndrome and benign positional vertigo did not differ significantly from those of the normal group (see Figs. 3, 4).

Although similar to those of the normal group, fluctuations of the SP/AP ratios were apparent and invariably showed a discordant pattern: When the SP voltage increased, the AP voltage did not necessarily follow, and vice versa. In Ménière's disease, pre–COO syndrome, and COO syndrome, this discordant pattern of the SP and AP voltages typically showed an increase of the SP voltage, whereas the AP voltage decreased (Fig. 7).

In benign positional vertigo, the discordant pattern of the SP voltage and AP voltage was reversed. The SP voltage decreased while the AP voltage increased, always being apparent on two occasions: once during the Trendelenburg positioning and again at the end of the stress test, on resuming starting position (Fig. 8). All patients in this group suffered from benign posterior canal vertigo. We did not have patients presenting with benign lateral canal vertigo.

Stress Electrocochleography
Perilymphatic Fistula

Patient T.B. **DOB** 23-08-42 **Date** 05-01-99



Interamplitudes (μV)

	SP	AP	SP BSL	AP	BSL	SP / AP
A8	-	-	+0.90	+1.37	Pre	0.19
A9	↑	↑	+0.60	+1.65	T_1	0.24
A0	⬆	⬇	+0.89	+1.60	T_2	0.40
B1	↓	↓	+0.54	+1.20	T_3	0.45
B2	↓	↓	+0.19	+1.11	Supine	0.17
B3	⬆	⬇	+0.64	+0.85	Q	0.75
B4	↑	↑	+0.42	+1.20	Post 30°	0.34

Figure 9. Stress electrocochleogram in round-window fistula. Discordance of SP and AP voltages is particularly noticeable during Queckenstedt maneuvers.

Raised intracranial pressure after the Queckenstedt maneuver showed a gradual increase of the SP/AP ratio starting with the pre–COO syndrome and followed by benign positional vertigo, COO syndrome and, finally, Ménière's disease (see Fig. 5). The SP/AP ratio in this group showed a marked increase of SP voltages and AP voltages. This pattern could be observed in both the normal group and the symptomatic patients, with the exception of patients with a perilymphatic fistula.

We had only two patients with a confirmed perilymphatic fistula and one patient with a suspected perilymphatic fistula. In all three patients, the increase of the SP/AP ratio was fairly marked (SP/AP ratios, 75%, 88% and 104%, respectively), but the pattern was discordant: The SP voltage increased while the AP voltage decreased considerably (Fig. 9). All three patients received ventilation tubes. The two females did not respond, and their repeat Queckenstedt electrocochleogram continued to show a discordant pattern of the SP and AP voltages. A middle-ear exploration confirmed a fistula in the round windows.

One male patient was suspected of having a perilymphatic fistula. However, after insertion of a ventilation tube, the repeat Queckenstedt electrocochleogram did not confirm the discordant pattern of the SP/AP ratio, which had returned to expected levels. Clinically, this patient felt better, and a middle-ear exploration was not attempted.

DISCUSSION

The description of the COO syndrome and its successful management with middle-ear ventilation tubes has rendered apparent that the inner ear can be extremely pressure-sensitive. This susceptibility is significant considering that the ventilation tube treats a mild eustachian tube dysfunction that is detectable only by specific tests.

Electrocochleograms have been studied under the influence of ambient and external ear canal pressure changes, but the results are not conclusive and are contradictory. Storms et al. [3] found no significant changes in the electrocochleograms of a normal population after exposure to positive pressure in the external ear canal. Changes in the electrocochleogram were seen in patients with Ménière's disease or endolymphatic hydrops. Although the SP/AP ratios improved with increased pressure, they did not normalize and were not associated with improvement of symptoms. Densert et al. [4] found that electrophysiological parameters in Ménière's disease patients are improved by the application of positive pressure pulses introduced to the middle ear through a ventilation tube. No changes were observed in the electrocochleograms after insertion of a ventilation tube.

We disagree with Densert's observations on the basis of our experience with the responsiveness of the COO syndrome to the insertion of a ventilation tube and our findings of a 67% response in Ménière's disease patients to the same procedure (see Table 1) with return of the baseline-electrocochleogram to normal levels.

The findings of Storms et al. [3] suggest that his method possibly was not sensitive enough. Indeed, pressure changes within the external ear canal may not have the same effect on the inner ear as pressure changes within the middle ear itself.

Normal Subjects

In our series, whether middle-ear pressure was increased or decreased did not matter. Changes of middle ear pressure always resulted in an increase of the SP/AP ratio. This outcome does seem to indicate that the inner ear is sensitive to changes of middle-ear pressure.

Statistically, the inner ear appeared more sensitive to changes of negative middle-ear pressure than to changes of positive middle-ear pressure. This indeed is consistent with the clinical observation that patients with Ménière's disease frequently complain of disturbed balance while descending in an aircraft but rarely during ascending.

An explanation for the response of the inner ear to changes of pressure—be it from the middle ear or through the cochlear aqueduct—could be deduced from the "Electromodel of the Auditory System" of Offutt [5]. In his treatise, Offutt described the tectorial membrane as piezoelectric, the potentials of which are sensed by the electrosensitive inner hair cells. Any static pressure exerted on a piezoelectric structure is suited to alter surface potentials by a simple shift of ions, which in this case would be detected by inner hair cells and consequently changing SP voltages. The sensitivity of the inner ear to changes of middle-ear pressure also highlights the necessity to know the middle-ear status prior to electrocochleography, as changes in middle-ear pressure could contaminate the SP/AP ratio.

In normal subjects, changes of the SP/AP ratio were observed not only during various constellations of middle ear pressure but during changes of intracranial pressure. Both Trendelenburg positioning and the Queckenstedt maneuver showed changes in the SP/AP ratios. The fluctuations of the SP/AP ratio observed during Trendelenburg positioning and the significant increase of the SP/AP ratio after the Queckenstedt maneuver, however, remained within 30%. These fluctuations of the SP/AP ratio are suspected to result from fluctuations of intracranial pressure during Trendelenburg positioning, and they might result from compensatory mechanisms to keep changes of brain circulation at a minimum.

The transfer of intracranial pressure to the inner ear, either through Trendelenburg positioning or the Queckenstedt maneuver, would be possible only when pressure waves can reach the fluid compartments of the inner ear. Therefore, we predict that an absence of fluctuations of the SP/AP ratio or absence of a significant rise of the SP/AP ratio would indicate a closed cochlear aqueduct.

A constant observation in normal subjects during Trendelenburg positioning and the Queckenstedt maneuver was a congruent pattern of the SP and AP voltages (i.e., when the SP voltage increased, so did the AP voltage, and vice versa). A significant increase of the SP/AP ratio always occurred during the Queckenstedt maneuver. The voltage ratio never decreased.

The congruent pattern of the SP and AP voltages in Trendelenburg positioning and the Queckenstedt maneuver was unique to normal subjects and fairly different in symptomatic patients. Studying this pattern of the SP and AP voltages appeared more helpful in the differential diagnosis of symptomatic patients than in comparing individual ratios of each group.

Patients with Ménière's Disease and Perilymphatic Fistula

In patients with pre-COO syndrome, COO syndrome, and Ménière's disease, SP voltages and AP voltages tended to show a discordant pattern during Trendelenburg positioning. Typically, the SP voltage initially would increase while the AP voltage would decrease. This reaction is unexpected, considering that inner hair cells synapse with afferent neurons of the auditory nerve.

Owing to the SP/AP ratio fluctuations that were observed in Trendelenburg positioning in all groups, we do not believe that this phenomenon results from a hydrops. We rather speculate that an ion shift, particularly potassium, would be suited to intoxicate auditory neurons temporarily. Horner [6] emphasized this action as a possible mechanism in Ménière's disease. This assumption also would explain the dramatic decrease of the AP voltage in the Queckenstedt maneuver that can be observed in a round-window fistula. In this fistula, a shift of ions would be expected as perilymph from the scala vestibuli—richer in potassium than is the scala tympani—is directed toward the round window. In the absence of a transmembranous fistula, the shift of ions would be possible through an enhanced intramembranous shunt at the round window, giving the mistaken impression of a true fistula. Arnold et al. [7] demonstrated in animal experiments that this pathway and direction of the perilymph flow exist.

Our experience with round-window fistulas is in agreement with the findings of Gibson [8] describing a decrease of the AP voltage with raised intrathoracic pressure during full anesthetic surgery. We believe, however, that the Queckenstedt electrocochleogram would be a suitable replacement and that suction at the round window would not be necessary. We suspect that the latter always will be positive for a round-window fistula, even in the presence of an intramembranous shunt. From our experience with the Queckenstedt electrocochleogram and taking Horner's potassium shift into consideration, we would deduct that a round-window fistula will present with reduction of AP voltages, whereas an oval-window fistula will show an increase of AP voltages.

Patients with Benign Positional Vertigo

In patients with benign positional vertigo, a discordant pattern of the SP and AP voltages is reversed (i.e., while the SP voltage decreases, the AP voltage increases). This phenomenon is apparent during Trendelenburg positioning and again in reversing the Trendelenburg position. An explanation for this phenomenon also is speculative. Our experience with electrovestibulography, which shows a very distinct AP voltage but a very small SP voltage (detection of which is difficult) would suggest that additional AP voltages are recorded from the vestibular nerve (Fig. 10). However, the voltage from the ampulla cannot be recorded, as it might be too small or too distant from the recording extratympanic electrode. Interestingly, stress electrocochleograms return to normal after a successful Epley repositioning maneuver.

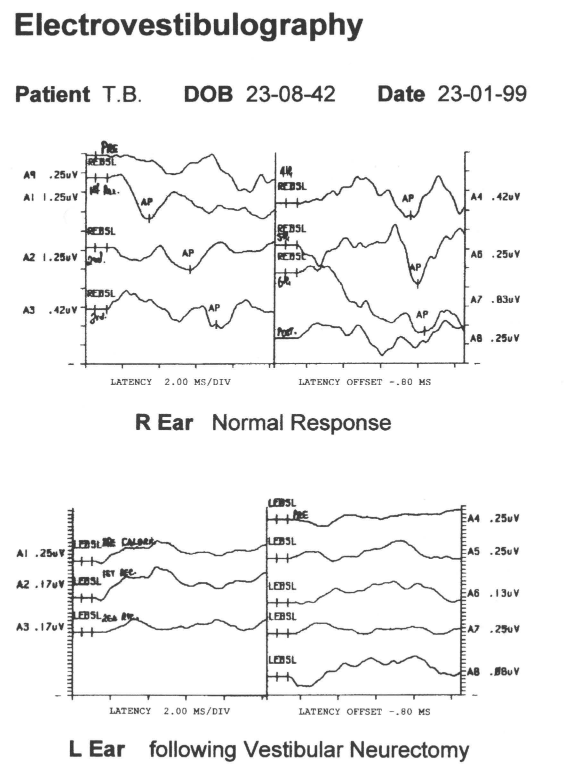


Figure 10. Electrovestibulogram showing a normal response in the right ear as compared to the left ear after vestibular neurectomy. The AP voltage is well defined, and detecting the SP voltage is difficult with an extratympanic electrode. Baseline activity is detectable only in the left ear.

CONCLUSION

Stress electrocochleography has become a valuable addition in the armamentarium of neurootological tests. The presenting syndromes show diverse patterns in baseline eletrocochleography and during the stress maneuvers. We find that looking for congruency or discordance of the SP/AP ratios during Trendelenburg positioning and the Queckenstedt maneuver are the most valuable parameters in the differential diagnosis of Ménière's disease.

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