
Effect of Static Middle-Ear and Intracranial Pressure Changes on Differential Electrocochleographic Response

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Abstract: In an animal model, we examined the extratympanic electrocochleographic response to static pressure changes (middle-ear pressure and intracranial pressure [ICP]) with attention to the summing potential (SP), action potential (AP), and the SP/AP ratio. With a closed middle ear, raised or lowered middle-ear pressure and raised or lowered ICP resulted in congruent increases of the SP and the SP/AP ratio, while the AP remained at a steady voltage. With a closed middle ear, raising or lowering ICP by positioning also had the effect of raising or lowering middle-ear pressure. With an open middle ear, raising or lowering middle-ear pressure resulted in congruent increases of the SP and the SP/AP ratio and, though the AP remained steady, it showed much higher voltage values. With an open middle ear, the baseline SP and baseline SP/AP ratio were reduced, but the reduction of the SP/AP ratio was mainly due to an increased AP. With an open middle ear, the SP, the SP/AP ratio, and the AP did not change appreciably during positioning-induced ICP changes. This suggests that ICP changes by positioning are not very effective in the rat when the middle ear is open. Thus, the effect of ICP changes with the middle ear closed are mainly due to positioning-induced pressure changes in the middle ear. Our findings confirm that static middle-ear pressure is critical for the cochlea and that good eustachian tube function is essential to keeping the pressure gradient across the round-window membrane as small as possible, the latter possibly assisted by a Windkessel function of the round-window membrane. However, relatively small pressure changes in the middle ear can overwhelm it, which suggests a very limited Windkessel function. In Ménière's disease, sensitivity to static pressure changes is possibly exaggerated. The insertion of a middle-ear ventilation tube, as practiced in treating selected cases of Ménière's disease, could restore Windkessel function. It has a stabilizing effect, as the inner ear appears less pressure-sensitive. This effect decreases Ménière's disease symptoms, but it is not without consequences. After the insertion of a middle-ear ventilation tube, a reduced SP/AP ratio is no evidence of improved inner-ear function. Its consequences are enlarged AP voltages, very likely loss of middle-ear dampening, and possible increased ringing.

Key Words: electrocochleography; intracranial pressure; Ménière's disease; middle-ear pressure; middle-ear ventilation tube; Windkessel function

The beneficial effect of the insertion of a middle-ear ventilation tube in the management of Ménière's disease is controversial. Tumarkin [1] first realized the inner ear's pressure sensitivity to static

pressure changes and suggested that endolymphatic hydrops is associated with reduced middle-ear ventilation via the eustachian tube. Since then, attempts have been made to treat Ménière's disease with the insertion of a middle-ear ventilation tube. A clinical study by Lall [2] was not very encouraging, nor was a study on eustachian tube functions in Ménière's disease by Hall and Brackmann [3]. They found no correlation between Ménière's disease and eustachian tube function.

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Montandon et al. [4] revived the concept of treatment with a middle-ear ventilation tube, and those authors were convinced that their affected patients' inner ears must be particularly sensitive to changes of middle-ear pressure. However, this group did not look at electrocochleographic parameters. Densert et al. [5] could demonstrate the inner ear's pressure sensitivity by electrocochleographic short-term effects of induced middle-ear pressure in Ménière's disease. Though hypobaric pressure previously proved to have a beneficial effect [6], whether it was owing to the insertion of a middle-ear ventilation tube by itself or to positive-pressure pulses, or to a combination thereof, was not clear. In this investigation, tone bursts stimulated restricted areas of the cochlea, implying that clicks, which stimulate the whole length of the cochlea, could have led to a different outcome.

Franz et al. [7] could demonstrate that raising intracranial pressure (ICP) and particularly reducing middle-ear pressure is followed by changes in the click-evoked electrocochleogram and that this could be useful in the differential diagnosis of inner-ear disorders. In a further study of endolymphatic hydrops, the inner ear's pressure sensitivity appeared reduced by the insertion of a ventilation tube. There, the reduction of the summing potential–action potential (SP/AP) ratio was due mainly to a raised AP [8].

Our experience with the insertion of a middle-ear ventilation tube and positive-pressure pulse therapy in the management of Ménière's disease confirms an exaggerated pressure sensitivity of the inner ear. Yet, why a middle-ear ventilation tube could possibly improve Ménière's disease symptoms remains unclear, as does whether the simple insertion of a ventilation tube would alter electrophysiological parameters of the cochlea. In an animal study, we were particularly looking at the inner ear's extratympanic electrocochleographic response to positive and negative changes of static middle-ear pressure while keeping the middle ear closed or open. After these experiments, we were interested in the electrocochleographic response of the inner ear to changes of ICP. We suspected an effect because the inner ear connects to intracranial fluid.

METHOD

We performed extratympanic electrocochleography (Biologic Navigator, Chicago, IL) on adult Sprague Dawley rats weighing 250–450 g. The tympanic recess harbored the active electrode, while the pinna and the vertex were the location for the reference electrode and the ground electrode, respectively. We stimulated the ear with clicks at an intensity of 90 dB, averaging 250 sweeps in each experiment. Four averaged and consecutive recordings

formed a block to determine the SP, the AP, and the SP/AP ratio. Baseline measurements preceded and followed static middle-ear and ICP changes. In each animal, we measured and compared the response of the inner ear to a middle ear open (myringotomy, open bulla) or middle ear closed condition (intact eardrum). A small myringotomy opened the eardrum anteroinferiorly. Clicks were delivered through the ear tip that sealed the external ear canal and was connected to an impedance bridge (Madsen, Model ZS-77-MB, Denmark). Positive or negative middle-ear pressure while keeping the middle ear closed was achieved with the help of swallowing, which was induced by stimulating the superior laryngeal nerve with a hook electrode (1–3V, 10 Hz, 500 msec). A gradual and stepwise reduction of middle-ear pressure via the external ear canal and an open middle ear delivered a pressure response curve. Positioning the animal raised or lowered ICP. It was reasonably assumed that the head-down position (–30 degrees) would increase ICP, whereas the head-up position (+30 degrees) would lower ICP. We compared results with those previously obtained from patients suffering from Ménière's disease before and after the insertion of a middle-ear ventilation tube. The averaged results of each group were compared using unpaired *t*-tests, with $\alpha = 0.05$.

RESULTS

Electrocochleogram

Clicks were delivered at an intensity of 90 dB through an ear tip that sealed the external ear canal in the rat. The ear tip was also connected to an impedance bridge to enable pressure changes in the middle ear or external ear canal. Four averaged and consecutive recordings formed a block to determine the SP, the AP, and the SP/AP ratio using the same criteria as is familiar in humans (Fig. 1).

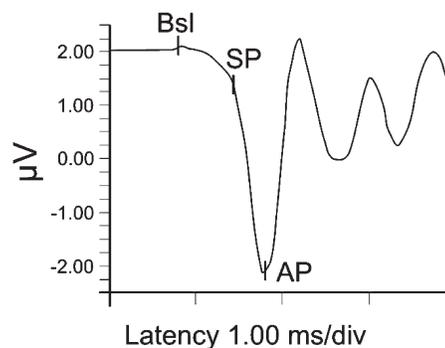


Figure 1. Normal electrocochleogram of a baseline assessment of an anesthetized rat (middle ear closed). The SP, AP, and SP/AP ratio were determined using the same criteria as is customary in evaluating cochlear function in humans. (*Bsl* = baseline; *SP* = summing potential; *AP* = action potential.)

Changing Middle-Ear Pressure with Swallowing, Middle Ear Closed

We induced changes in middle-ear pressure by increasing pressure in the external ear canal of anesthetized rats. This would cause an inward flexion of the tympanic membrane and raised middle-ear pressure. The animal was then induced to swallow to equalize middle-ear pressure, releasing pressure in the external ear canal. The net outcome was a small negative pressure in the middle ear. Thus, positive pressure (+300 decapascal) in the external ear canal, with a simultaneous swallow, resulted in mild negative middle-ear pressure. Negative pressure (−300 decapascal) in the external ear canal, with a simultaneous swallow, resulted in mild positive middle-ear pressure. Pressure changes in the middle ear averaged −15.9 decapascal (SD, ±18.6 decapascal; $n = 4$) with positive pressure in the external ear canal and +19.2 decapascal (SD, ±10.9 decapascal) with negative pressure in the external ear canal.

Whether we created mild positive or mild negative pressure in the middle ear did not matter; the response of the SP and the SP/AP ratio was congruent. The SP and the SP/AP ratio increased while positive or negative pressure was maintained in the middle ear. The AP remained steady during the experiment (Fig. 2).

Changing Middle-Ear Pressure via the External Ear Canal, Middle Ear Open

We induced changes in middle-ear pressure (± 300 decapascal) with an open eardrum via an ear tip sealed in the external ear canal. With the open middle ear, whether there was positive or negative pressure in the external ear canal did not matter; the response of the SP and the SP/AP ratio was congruent. These increases of the SP and the SP/AP ratio were slightly, but not significantly, smaller than with the middle ear closed. The baseline SP overall was smaller with an open middle ear. The AP remained steady, but it showed much higher voltage values when compared to the previous experiment with the middle ear closed. The reduction of the SP/AP ratio with an open middle ear, however, was predominantly due to a higher AP voltage value (Fig. 3).

Effect of ICP, Middle Ear Closed

We assumed that lowering or raising the head of the animal would raise or lower ICP. As these maneuvers have been shown in the human to change not only ICP but also middle-ear pressure, we expected a similar observation in the animal [9]. The animal was positioned ± 30 degrees, and change of middle-ear pressure was measured with the impedance bridge. Changes of middle-ear pressure were mild and comparable to pres-

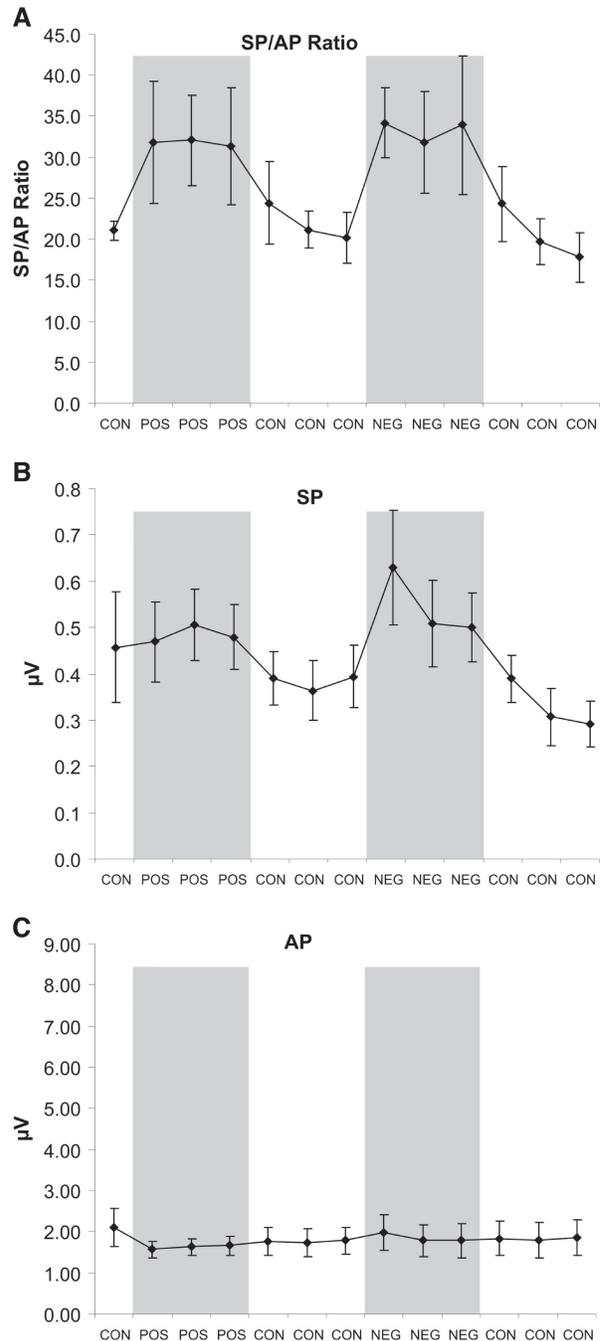


Figure 2. Electrocochleography readings for the right ear of an anesthetized rat. Middle-ear pressure was set by changing the pressure in the external ear canal, stimulating a single swallow, and then returning the external ear canal to ambient pressure. Note that responses are congruent (CON) for the SP/AP ratio (A) and the SP (B) for both positive (POS) and negative (NEG) pressure in the middle ear, while the AP (C) remains steady and low. (SP = summating potential; AP = action potential.)

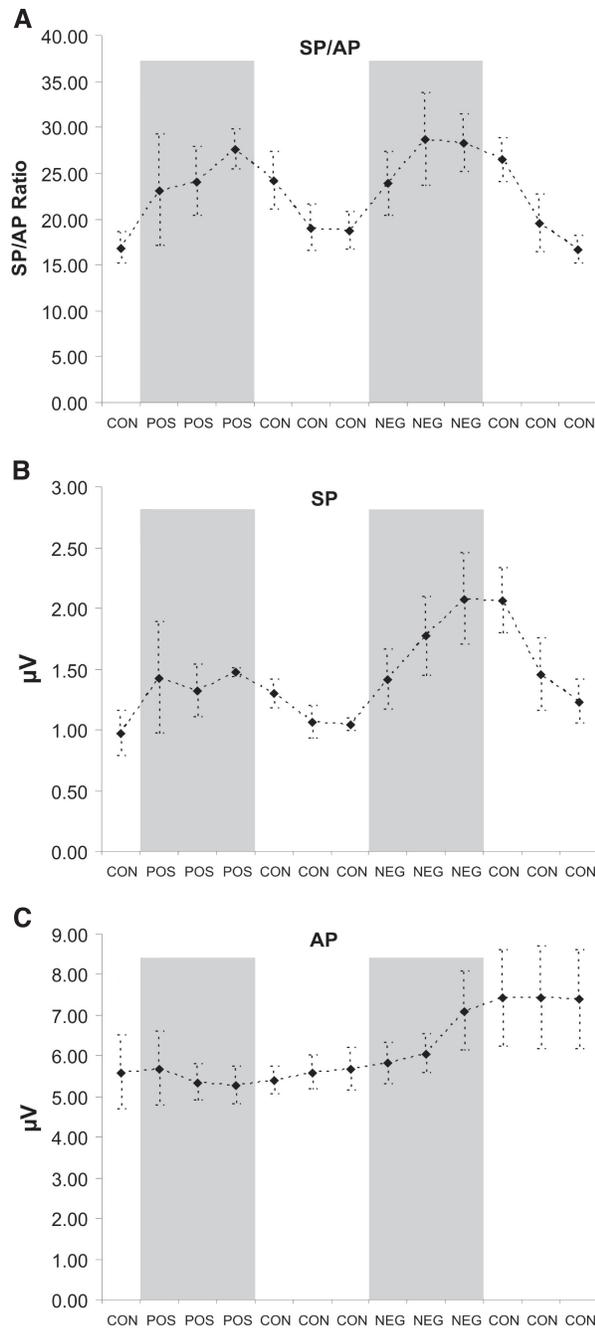


Figure 3. With an open eardrum, positive (*POS*) or negative (*NEG*) pressure in the middle ear applied through the external auditory canal evoked a congruent (*CON*) response of the SP and the SP/AP ratio, but the AP remained high at all times. (*SP* = summing potential; *AP* = action potential.)

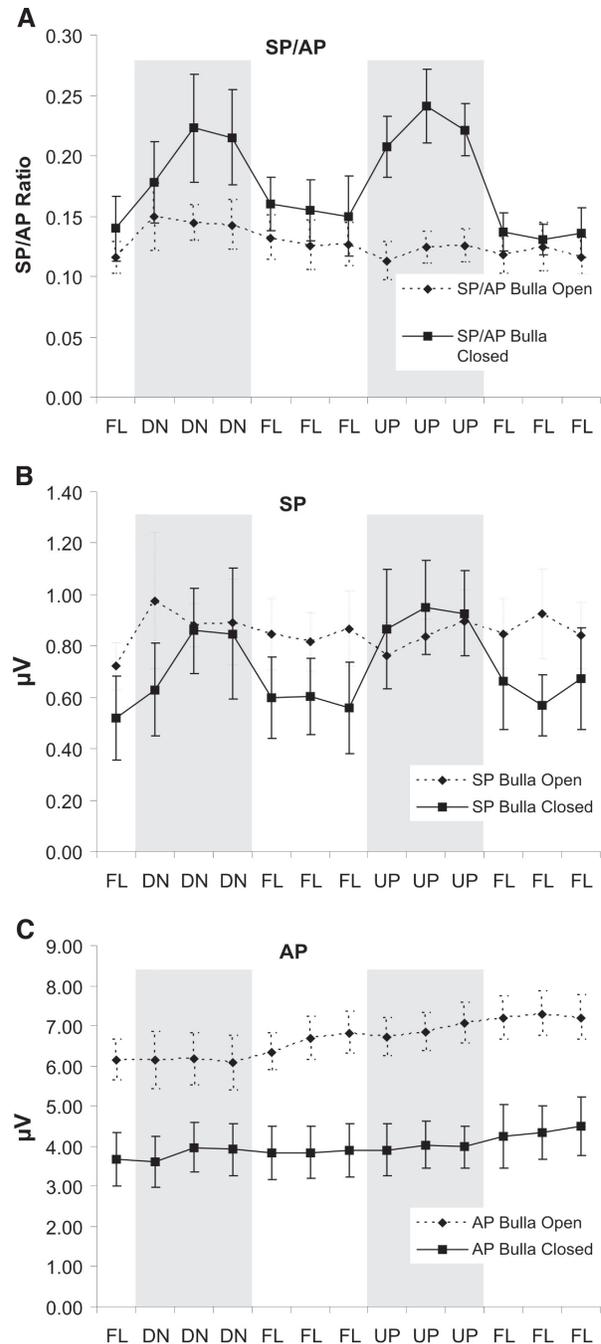


Figure 4. With a closed middle ear, positioning the animal with head down (*DN*; increasing intracranial pressure) or head up (*UP*; decreasing intracranial pressure) resulted in a congruent increase in the SP/AP ratio (*A*) and SP (*B*), while the AP (*C*) remained steady. With an open middle ear, positioning the animal with head down and head up resulted in no change in the SP and the SP/AP ratio. The AP remained unresponsive to tilting but showed higher voltage values when the middle ear was open. The SP was slightly increased, but it was insufficient to raise the SP/AP ratio. Instead, the dramatic increase of the AP reduced the SP/AP ratio. (*SP* = summing potential; *AP* = action potential; *FL* = animal lying flat.)

sure changes induced by swallowing. Lowering the head of the animal averaged +15.9 decapascal (SD, ± 7.9 decapascal; $n = 4$), and raising the head resulted in -25 decapascal (SD, ± 10.7 decapascal; $n = 4$).

Positioning the animal with head down (increasing ICP) and head up (decreasing ICP) resulted in a congruent increase of the SP and the SP/AP ratio, while the AP remained steady (Fig. 4). This response was equal to the response with raised and lowered middle-ear pressure with a closed middle ear.

Effect of ICP, Middle Ear Open

In this portion of the experiment, the eardrum was left intact, and the middle ear was opened via a hole drilled into the bulla. Positioning the animal with head down and head up resulted in insignificant changes of the SP and the SP/AP ratio. However, the AP again showed higher voltage values when the middle ear was open. The SP was slightly increased, but it was insufficient to raise the SP/AP ratio. Instead, a dramatic increase of the AP reduced the SP/AP ratio (see Fig. 4).

Pressure Response Curve, Middle Ear Open

To obtain a pressure response curve, middle-ear pressure was gradually reduced via the external ear canal with an open eardrum. We chose negative pressures, as it prevented a spontaneous opening of the eustachian tube. Any pressures below -40 decapascal resulted in minor changes of the SP and the SP/AP ratio up to -80 decapascal (Fig. 5).

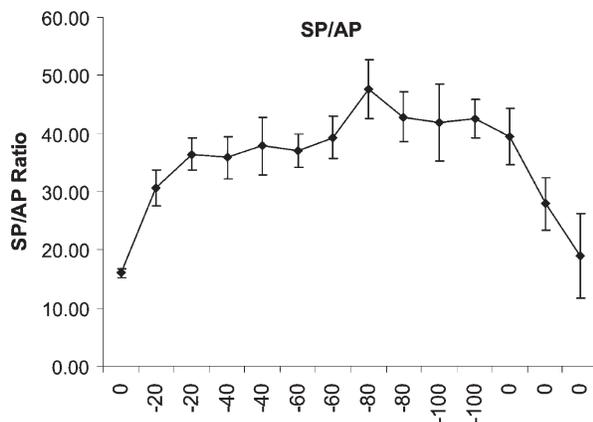


Figure 5. Summating potential–action potential (SP/AP) ratio for a range of negative pressures (in decapascal) applied from the external auditory canal through an open eardrum in an anesthetized rat to create a pressure response curve. The use of negative pressures in the middle ear prevented a spontaneous opening of the eustachian tube. Note the responsiveness of the SP/AP ratio to small pressure changes. Pressure changes smaller than -20 decapascal could not be explored owing to limitations of the equipment.

Thereafter, further pressure decreases led to a temporary jump in the SP/AP ratio until saturation reached about -100 decapascal. The SP and the SP/AP ratio returned quickly once the pressure in the middle ear normalized, but the ratios did not reach the levels as observed at the start of the experiment. The AP remained steady during the experiment. Major changes of responses were found particularly in the lower end of the scale.

DISCUSSION

Our animal studies confirm the inner ear's sensitivity to the change of static pressure in the middle ear. Immediate responses of the SP and the SP/AP ratio reflect this sensitivity, and whether the change of middle-ear pressure was positive or negative did not matter: Surprisingly, negative and positive pressures had the same effect. One explanation could be that both pressure constellations equally changed inner-ear mechanics.

The AP always remained steady. Thus, the change of the SP determined the SP/AP ratio. This suggested altered cochlear function in response to a change of middle-ear pressure.

Middle-ear pressure is critical, but the value of the SP/AP ratio per se is not necessarily a good indicator of the integrity of the inner ear without knowledge of middle-ear function. Our findings support Ferraro et al. [10]. In their studies on humans, the eardrum remained closed. Changes of pressure in the external ear canal altered pressure in the middle ear. As the middle-ear pressure constellation affected the outcome in electrocochleography, some suggested that this must be taken into consideration when interpreting test results.

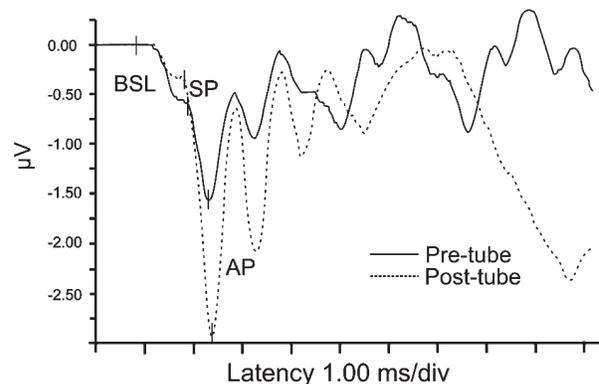


Figure 6. Electrocochleogram before and after the insertion of a middle-ear ventilation tube in a person suffering from Ménière's disease. Before the insertion of the middle-ear ventilation tube, the summating potential (SP) seems elevated, and the action potential (AP) appears small, rendering a high ratio. After the insertion of the middle-ear ventilation tube, a small change of the SP is seen, but the AP is dramatically elevated, resulting in a smaller SP/AP ratio. (BSL = baseline.)

With an open middle ear, we observed a similar response of the inner ear to pressure changes in the middle ear. There was an immediate response of the SP and the SP/AP ratio while the AP remained steady. However, the AP with an open middle ear had a much higher voltage value than with a closed middle ear. As the AP increase was already apparent in the baseline measurements, we argue that the simple opening of the middle ear and exposure to ambient pressure was responsible for an elevated AP.

A similar observation is made in humans. Figure 6 shows the results of a patient suffering from Ménière's disease before and after the insertion of a middle-ear ventilation tube. Before the insertion of the tube, the SP seems elevated and the AP appears small, rendering a high ratio. After the insertion of the ventilation tube, we observed a small change of the SP, but the AP was dramatically elevated, mainly being responsible for a smaller SP/AP ratio.

Therefore, the simple opening of the middle ear and exposure to ambient pressure appear to modify the response of the auditory nerve while maintaining pressure sensitivity of the cochlea. One possible explanation for the increase of the AP is altered middle-ear function (i.e., the loss of middle-ear dampening, possibly combined with increased ringing).

With the middle ear closed, raising or lowering ICP by positioning also engendered an immediate response of the SP and the SP/AP ratio, whereas the AP remained steady. These results compare well with raising or lowering middle-ear pressure with a closed middle ear. Again, whether the pressure was positive or negative did not matter. As raising or lowering ICP had the effect of raising or lowering middle-ear pressure, the static middle-ear pressure suggests that that is the critical parameter.

With the middle ear open, however, raising or lowering ICP by positioning provoked quite a different response. The SP and the SP/AP ratio changed only marginally, whereas the AP remained steady but elevated. The lack of response of the SP and the SP/AP ratio suggests that the pressure transfer to the inner ear (e.g., via the cochlear aqueduct) is restricted in the rat. Thus, changes observed with the middle ear closed were more likely due to changes of middle-ear pressure.

The pressure response curve confirms pressure sensitivity of the inner ear (see Fig. 6). The major changes of the SP and the SP/AP ratio at the lower end of the scale were unexpected. At the higher end of the scale, further increases of middle pressure above 80–100 decapascal showed little effect.

To keep the effect of static pressure changes in the middle ear to a minimum requires good eustachian tube function. An optimal operation of the inner ear would be

assisted by a Windkessel function of the round-window membrane.

The round window tends to ensure that the amplitude of pressure fluctuations within this system is kept as small as possible. However, small pressure changes of only 20 decapascal already exceed the ability of the round-window membrane to compensate, rendering the inner ear extremely sensitive to static pressure changes.

Opening the middle ear or inserting a middle-ear ventilation tube ensures that the middle ear remains at ambient pressure. It will be associated with a reduction of the SP/AP ratio, as the AP will increase as soon as the middle ear is opened. However, to suggest that a reduced SP/AP ratio reflects improved inner-ear function is possibly an illusion. The insertion of a middle-ear ventilation tube addresses pressure sensitivity, as changes of ambient pressure will equally impinge on the middle ear and the inner ear. In Ménière's disease, pressure sensitivity to changes of middle-ear pressure is most likely exaggerated. Thus, the insertion of a middle-ear ventilation tube will help to alleviate the symptomatology in Ménière's disease, but it is achieved at the expense of an increased AP and possible loss of an important feature of sound transmission of the middle ear, which is dampening.

CONCLUSION

Static pressure changes of the middle ear can be critical for the inner ear. Good eustachian tube function is essential to keeping pressure changes as small as possible. The round-window membrane might assist in keeping pressure changes low by a Windkessel function, but its effect is very limited. Opening the middle ear or inserting a middle-ear ventilation tube, as performed in selected cases of Ménière's disease, will render the inner ear less pressure-sensitive and has a stabilizing effect. However, it may come at the expense of losing an important feature of sound transmission, which is dampening. A reduced SP/AP ratio after the insertion of a ventilation tube is mainly due to a raised AP, and the reduction of the SP/AP ratio does not necessarily reflect improved inner-ear function.

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