vestibule or at the scala vestibuli. This result is consistent with clinical data of patients suffering from PLF (Goto et al., 2001). At low frequencies, the pressure generated in the cochlea with a fistula becomes lower than the pressure in the intact cochlea because the lymphatic fluid easily flows in and out through the fistula. By contrast, at high frequencies, the movement of the lymphatic fluid depends on the inertia of the lymphatic fluid itself rather than on the boundary condition surrounding the lymphatic fluid. This is a reason why the changes in the vibration of the BM at high frequencies are smaller than those at low frequencies.

Meanwhile, when a fistula existed adjacent to the RW, the maximum amplitude was not changed significantly even though the size of the fistula adjacent to the RW is larger than that of the fistula at other places (Table 3). Foster and Luebke (2002) reported that the RW fistula itself does not cause hearing loss, and air bubbles entered into the cochlea from the fistula. Our findings are in agreement with this result. The RW membrane is far more mobile than the bony wall of the cochlea, and the lymphatic fluid at the vicinity of the RW can naturally flow easily. In other words, the RW can be regarded as a large fistula. This is the reason why a fistula near the RW does not affect the vibration of the BM. On the other hand, Kelly and Khanna (1984) reported that opening the round window caused histological damage in the apical region of the BM presumably due to a large momentary pressure differential created across the organ of Corti. This damage was similar to that induced by low-frequency sound and may cause the loss of sensitivity of the BM (Leonard and Khanna, 1984). In our present analysis, the damages of the organ of Corti and the BM have not been considered, and hearing loss was estimated based on only the attenuation of the BM vibration. To clarify the actual mechanism of hearing loss caused by a perilymphatic fistula, the effects of the histological damages should most likely be considered in the future.

5. Conclusions

In this study, a three-dimensional finite-element model of the human cochlea was created. Passive dynamic behavior of the BM, which is closely related to auditory activity at moderate to high SPLs, and the cochlear fluid caused by the vibration of the stapes footplate were analyzed. When a fistula exists at the vestibule or at the scala vestibuli, the maximum amplitude of the BM becomes smaller than that in the intact cochlea. The losses in the amplitude increased with decreasing frequency. In particular, when the fistula exists at the basal part of the scala vestibuli, the effect extends to high frequencies. By contrast, when a fistula exists at the vicinity of the RW, the vibration of the BM scarcely changes. This model assists in elucidating mechanisms of hearing loss due to a PLF, and is useful in the establishment of new treatments for the PLF.

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References

Andoh, M., Wada, H., 2004. Prediction of the characteristics of two types of pressure waves in the cochlea: theoretical considerations. J. Acoust. Soc. Am. 116, 417–425.
Andoh, M., Nakajima, C., Wada, H., 2005. Phase of neural excitation relative to basilar membrane motion in the organ of corti: theoretical considerations. J. Acoust. Soc. Am. 118, 1554–1565.
Becvarovski, Z., 2004. Absorption of intratympanic topical antibiotics. Ear Nose Throat J. 83 (9 Suppl. 4), 18–19.
Böhnke, F., Arnold, W., 1999. 3D-finite element model of the human cochlea including fluid-structure couplings. ORL J. Otorhinolaryngol. Relat. Spec. 61, 305–310.
Cabezudo, L.M., 1978. The ultrastructure of the basilar membrane in the cat. Acta Oto-Laryngol. 86, 160–175.
Dreiling, F.J., Henson, M.M., Henson Jr., O.W., 2002. The presence and arrangement of type II collagen in the basilar membrane. Hear. Res. 166, 166–180.
Foster, P.K., Luebke, A.E., 2002. A model for perilymphatic fistula induced hearing loss in the guinea pig cochlea. Hear Res. 167, 175–179.
Fleischer, M., Schmidt, R., Gummer, A.W., 2010. Compliance profiles derived from a three-dimensional finite-element model of the basilar membrane. J. Acoust. Soc. Am. 127 (5), 2973–2991.
Goto, F., Ogawa, K., Kunihiro, T., Kurashima, K., Kobayashi, H., Kanzaki, J., 2001. Perilymph fistula – 45 case analysis. Auris Nasus Larynx 28 (1), 29–33.
Greenwood, D.D., 1990. A cochlear frequency-position function for several species-29years later. J. Acoust. Soc. Am. 87, 2592–2605.
Igarashi, M., Ohashi, K., Ishii, M., 1986. Morphometric comparison of Endolymphatic and perilymphatic spaces in human temporal bones. Acta Otolaryngol. 101, 161–164.
Ikezono, T., Shindo, S., Sekiguchi, S., Morizane, T., Pawankar, R., Watanabe, A., Miura, M., Yagi, T., 2010. The performance of cochlin-tomoprotein detection test in the diagnosis of perilymphatic fistula. Audiol Neurotol. 15, 168–174.
Iurato, S., 1962. Functional implications of the nature and submicroscopic structure of the tectorial and basilar membranes. J. Acoust. Soc. Am. 34, 1386–1395.
Kelly, J.P., Khanna, S.M., 1984. Distribution of cochlear damage caused by the removal of the round window membrane. Hear Res. 16 (2), 109–126.
Koike, T., Wada, H., Kobayashi, T., 2002. Modelling of the human middle ear using the finite-element method. J. Acoust. Soc. Am. 111, 1306–1317.
Leonard, D.G.B., Khanna, S.M., 1984. Histological evaluation of damage in cat cochlea used for measurement of basilar mechanics. J. Acouht. Soc. Am. 75, 515–527.
Lighthill, J., 1981. Energy flow in the cochlea. J. Fluid Mech 106, 149–213.
Lim, K.M., Steele, C.R., 2002. A three-dimnesional active cochlea model analyzed by the WKB-numeric method. Hear. Res. 170, 190–205.
Lim, Y.S., Park, Se-Ik, Kim, Y.H., Oh, S.H., Kim, S.J., 2005. Three-dimensional analysis of electrode behavior in a human cochlear model. Mech. Eng. Phys. 27, 695–703.
Manoussaki, D., Chadwick, R.S., 2000. Effects of geometry on fluid loading in a coiled cochlea. SIAM J. Appl. Math. 61, 369–386.
Meaud, J., Grosh, K., 2010. The effect of tectorial membrane and basilar membrane longitudinal coupling in cochlear mechanics. J. Acoust. Soc. Am. 127 (3), 1411–1421.
Merchant, S.N., Rosowski, J.J., 2008. Conductive hearing loss caused by third-window lesions of the inner ear. Otol. Neurotol. 29, 282–289.
Merchant, S.N., Raviz, M.E., Rosowski, J.J., 1996. Acoustic input impedance of the stapes and cochlea in human temporal bones. Hear. Res. 97, 30–45.
Merchant, S.N., Adams, J.C., Nadol Jr., J.B., 2005. Pathology and pathophysiology of idiopathic sudden sensorineural hearing loss. Otol. Neurotol. 26, 151–160.
Nishioka, I., Yanagihara, N., 1986. Role of air bubbles in the perilymph as a cause of sudden deafness. Am. J. Otol. 7 (6), 430–438.
Nomura, Y., Hara, M., 1986. Experimental perilymphatic fistula. Am J Otolaryngol. 7 (4), 267–275.
Nomura, Y., Okuno, T., Hara, M., Young, Y.H., 1992. Floating labyrinth. Pathophysiology and treatment of perilymph fistula. Acta Otolaryngol. 112, 186–191.
Parthasarathi, A.A., Grosh, K., Nuttall, A.L., 2000. Three-dimensional numerical modeling for global cochlear dynamics. J. Acoust. Soc. Am. 107 (1), 474–485.
Ramamoorthy, S., Deo, N.V., Grosh, K., 2007. A mechano-electro-acoustical model for the cochlea: response to acoustic stimuli. J. Acoust. Soc. Am. 121 (5), 2758–2773.
Ren, T., 2002. Longitudinal pattern of basilar membrane vibration in the sensitive cochlea. PNAS 99 (26), 17101–17106.
Schweitzer, L., Lutz, C., Hobbs, M., Weaver, S., 1996. Anatomical correlates of the passive properties underlying the developmental shift in the frequency map of the mammalian cochlea. Hear. Res. 97, 84–94.
Simmons, F.B., 1979. The double-membrane break syndrome in sudden hearing loss. Laryngoscope 89, 59–66.
Skrodzka, E.B., 2005. Mechanical passive and active models of the human basilar membrane. Appl. Acoust. 66, 1321–1338.
Steele, C.R., Taber, L.A., 1979. Comparison of WKB and finite difference calculations for a two-dimensional cochlear model. J. Acoust. Soc. Am. 65, 1001–1006.
Stenfelt, S., Puria, S., Hato, N., Goode, R.L., 2003. Basilar membrane and osseous spiral lamina motion in human cadavers with air and bone conduction stimuli. Hear. Res. 181, 131–143.
Ulehlova, L., Voldrich, L., Janisch, R., 1987. Correlative study of sensory cell density and cochlear length in humans. Hear. Res. 28, 149–151.
Weisskopf, A., Murphy, J.T., Merzenich, M.M., 1978. Genesis of the round window rupture syndrome; some experimental observations. Laryngoscope 88, 389–397.
Wever, E.G., 1949. Theory of Hearing. John Wiley and Sons, Inc., New York.
Yoon, Y.J., Puria, S., Steele, C.R., 2007. Intracochlear pressure and derived quantities from a three-dimensional model. J. Acoust. Soc. Am. 122 (2), 952–966.

Web reference

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